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Thirteenth Moving Base
Gravity/Gradiometer Conference
United States Air Force Academy
Colorado Springs, Colorado

Agenda

Tuesday 12 February

0730 - Buses depart USAFA Officers' Club for Fairchild Hall

0745 - Late Registration - 3rd floor Fairchild Hall, South End

0815 - Welcome/Introduction - 1Lt Donna Warner

0820 - Opening Remarks - Dr. Charles Martin (DMA)

0830 - Gravity Gradiometer Survey System Program Status Review - Mr. Richard Borgeson (AFGL)

0850 - Review of Moving Base Gravity Survey System (Navy) at Bell Aerospace - Mr. Ernest Metzger (Bell)

0920 - Review of Moving Base Gravity Gradiometer Survey System (Air Force) - Mr. Lou Pfohl (Bell)

0950 - Break

1010 - GGSS Data Analysis Review - Dr. Christopher Jekeli (AFGL)

1025 - GGSS Test Planning and Test Data Treatment - Dr. Warren Heller (TASC)

1055 - Contribution of Terrain in Phase II Test Area to Disturbance of Gradients Measured Aloft - Mr. C. Lawrence Bradley (Geospace)

1110 - The Template Method for GGSS Data Reduction - Dr. Jake Goldstein (TASC)

1145 - Buses Depart Fairchild Hall for USAFA Officers' Club

1200 - Luncheon - Officers' Club

1300 - Buses Depart Officers' Club for Fairchild Hall

1315 - Synthetic Data Generation for Analysis of GGSS Stage II Reduction Techniques - Dr. Peter Ugincius (NSWC)

1345 - Post Mission Adjustment of Gravity Gradiometer Data - Mr. G. Scott Peacock (Geospace)

1415 - Frequency Domain Processing of Airborne Gravity Gradiometer Survey Data for Derivation of the Gravity Disturbance Spectrum - Dr. John Hutcheson (Bell)

1445 - Break

1505 - (a) On the Problem of Astrogeodetic-Gradiometric Vertical Deflection Determination in Mountainous Terrain
(b) A High Accuracy Astrogeodetic-Inertial Data Base for Tests of the Bell Gravity Gradiometer - Dr. H. Baussus von Luetzow (Army - ETL)

1535 - Analysis of the High Frequency Spectrum of the Anomalous Potential - Mr. Anthony A. Vassiliou (University of Calgary)

1615 - Buses depart Fairchild Hall for Officers' Club

1630 - Reception - USAFA Officers' Club

Wednesday 13 February

0745 - Buses Depart USAFA Officers' Club for Fairchild Hall

0800 - Two Dimensional Karhunen-Loeve Smoothing of Gravity Gradiometer Surveys - Dr. Sam Bose (Applied Science Analytics Inc.)

0830 - Deterministic and Stocastic Representation of Gravity Gradient Using Spherical Harmonics - Mr. Marvin May (NADC)

0850 - Review of Superconducting Accelerometer and Gravity Gradiometer Research at the University of Maryland - Dr. Ho Jung Paik (University of Maryland)

0930 - Break

Presentation of Classified Papers. Only persons with a security clearance of at least SECRET will be allowed to attend these presentations.

0950 - Basic Concepts in Real-time Processing of Gravity Gradiometer Data - Mr. William Chairetakis (Sperry)

1020 - Inferring Gradiometer Environmental Sensitivity From Long Term Test Data - Mr. Donald Benson (Dynamics Research Corporation)

1040 - Short Break

1050 - Techniques for Using Multiple Distributions in GGSS Stage II Data Reduction - Mr. Alan Rufty

1135 - DoD Executive Session

1215 - Buses leave

MINUTES OF THE THIRTEENTH ANNUAL
MOVING BASE GRAVITY GRADIOMETER CONFERENCE

United States Air Force Academy
Colorado Springs, Colorado

12-13 February 1985

Tuesday Morning Session

Welcome/Introduction - 1Lt Donna Warner (AFGL)
As coordinator of the two-day conference, Lt Warner opened the meeting on behalf of the co-sponsoring agencies, the Air Force Geophysics Laboratory (AFGL) and the Defense Mapping Agency (DMA). She then introduced Dr. C. Martin, Director of the Advanced Technology Division, DMA.

Opening remarks - Dr. Charles Martin
Dr. Martin welcomed participants and attendees. He made comments pertaining to the past, present, and future of gravity gradiometry. He made note of the Navy initiatives which generated interest in the field five years ago and how DMA is currently cooperating with them and the Air Force in pursuing research in surface and airborne measurement of gravity gradients. Dr. Martin forsees a need for accuracy of several orders of magitude greater, especially in conjunction with the space program. He concluded by introducing Dr. Randy Smith, DMA's Chief Scientist in Geodesy and Geophysics.

AFGL/DMA Program Review - Mr. Richard Borgeson (AFGL)
Mr. Borgeson, program manager of the Gravity Gradiometer Survey System, presented a review of what transpired in 1984 on the GGSS Program; the test site was selected, the aircraft was selected and tail number 151384 was accepted in January 1985. He then presented future milestones on the program: lab testing, aircraft testing, and system acceptance and delivery, among others.

Review of Moving Base Gravity Survey System (Navy) at Bell Aerospace - Mr. Ernest Metzger (Bell)
Mr. Metzger highlighted the major areas of activity on the Navy Gravity Survey System (GSS) Program. He described the system which contains 1 gravity sensor platform on which the gravity instruments are mounted, 1 GSS electronics cabinet, and 1 memory processor. He went into detail describing the microprocessor functions, the orientation of the GGIs, and the configuration of the electronics cabinet. Mr. Metzger reviewed the key milestones since the 1984 review stating that major progress was made in three areas 1) GGI slip ring assembly 2) GGI shock test and 3) error coeffecient calibration.

Review of Moving Base Gravity Gradiometer Survey System (Air Force) - Mr. Al Jircitano (for Mr. Lou Pfohl - Bell)
Mr. Jircitano first emphasized the survey and test programs for each phase, Phase I (land) and Phase II (air) of the GGSS Program. He identified the test methods and mentioned that data would be run through the Rolm MV10000 computer to decide whether or not to repeat a test. He showed the flow of analysis for the Phase II data reduction using the MV 100000. Mr. Jircitano

also discussed the GGI performance monitor.

Questions:
Mr. M. Molny (Sperry) - Which vehicle environment (land or air) is more severe?

Mr. Jircitano - Both are tough. Depends on many features including the operation of the vehicle.

Mr. Molny - Is it your intent to establish precise control of the track or to determine precise positons?

Mr. Jircitano - We're not surveying the track, but with GPS we will get accurate vehicle positions.

Mr. A. Carlson (DMAHTC/GST) - Why do you have four closely spaced astro points in Phase II land testing?

Mr. Jircitano - To determine short term variation of instrument performance.

GGSS Data Analysis Review - Dr. Christopher Jekeli (AFGL)
Dr. Jekeli reviewed Stage II of Phase II GGSS data processing. It entails the reduction of gravity gradients measured at aircraft altitude to estimates of the surface gravity disturbance vector. He mentioned alternatives to optimal estimation. Current efforts related to Stage II data processing are turning to comprehensive simulations to study the various processing algorithms. Several issues, such as data management, have yet to be addressed in detail.

Questions:
Mr. P. Ugincius (NSWC) - Is the PSD (on your graph) for the vertical gravity disturbance?

Dr. Jekeli - Yes

GGSS Test Planning and Test Data Treatment - Dr. Warren Heller (TASC)
Dr. Heller discussed the technical factors driving the design of the airborne test program, test-based validation of GGSS performance, and data treatment scenarios. These issues are related to our knowledge of the gravity field in the north Texas test area. He drew inferences as to the accuracy which the gradiometer is most likely to achieve in that location. Dr. Heller offered a summary perpective of the near future of moving base gravity gradiometry.

Questions:
Mr. Molny - Is the test directed toward instrument noise or gravity estimation? Why not use all the information?

Dr. Heller - The test is directed toward gravity estimation. Part of the test involves controlling variables and understanding them quantitatively.

A discussion between Decker, Metzger, Molny, and Heller followed concerning use of all the data points.

Mr. T. Sims (NSWC) - Can we get gravity to within 1 mGal anywhere in the inner zone?

Dr. Heller - We always have edge effects.

Mr. Sims - In reality is there an inner zone?

Dr. Heller - For comparison with truth data, I guess that's a way of thinking of it.

Dr. J. Katz (SSPO) - Is there any reason for choosing the Texas test area?

Lt Fundak (AFGL) - There is little topographic signature, high frequency gravity signature, and good truth data.

Dr. Katz - Is there any mandate that you survey over land?

Lt Fundak - Yes, the truth data is sufficiently accurate over land.

Mr. Carlson - Where does the active model come from?

Dr. Heller - Deep ocean trench data and high alpine area data. This represents the upper bound of gravity variation in any area.

Comment by Lou Decker (DMAAC) - Base line model is then not a world-wide average but a typical local model.

<u>The Template Method for GGSS Data Reduction</u> - Dr. Jacob Goldstein (TASC)
Dr. Goldstein presented an overview of the template method for GGSS data reduction. The method consists of first averaging the airborne gradiometer measurements on suitably chosen zones, and then processing these averages using optimal estimation techiques. He also discussed why the appropriate quantity to be estimated during GGSS testing is the residual gravity disturbance vector, which is defined as the departure of the point gravity disturbance from its local mean. Dr. Goldstein presented the results of applying the algorithm for estimating the vertical component of the residual gravity disturbance vector. The simulated data were obtained from a model tuned to the test area. The results of the simulation constitute an end-to-end check on algorithm consistency.

Questions:
Dr. Ugincius - Why do you get better results by excluding data?

Dr. Goldstein - Forcing average gains on some data may prove detrimental to the total solution. It is better to exclude some data than use it.

Dr. Bose (Applied Sciences Analytics Inc) - How is the noise characterized?

Dr. Goldstein - We assume white noise. Red noise can be taken out or reduced to the same level as white noise.

Dr. Bose - When W (width of averaging zone) goes to zero, do we get optimal estimation?

Dr. Goldstein - Yes.

Mr. Zorn (Dynamics Research) - How are errors in self gradient compensations accounted for?

Dr. Goldstein - Bell's error budget includes these errors.

Mr. Brozena (NRL) - On repeat track error model determination, how close do altitude and position have to be navigated?

Dr. Heller - Bell has an autopilot. Initial position can be re-established by resetting the barometric altimeter, and GPS data processing has to take into account day to day barometric surface. It will be difficult to stay within 200m in all coordinants for an 800km track.

Discussion ensued.

Tuesday Afternoon Session

Synthetic Data Generation for Analysis of GGSS Stage II Reduction Techniques - Dr. Peter Ugincius (NSWC)

Dr. Ugincius began with the explanation that NSWC has been tasked by DMA to provide the gravity gradiometry community with synthetic data. These data will provide a common basis for assessing and evaluating different computational methods that are proposed for reducing the gradient measurements in the GGSS program. NSWC has constructed for this purpose two different data bases:

1. Stochastic model with known statistics,

2. Deterministic (non-stochastic) features with superimposed stochastic short-wavelength signals.

The models consist of point masses and dipoles. Gravity gradients are computed on a plane 600m above the earth's surface on a grid specified by the survey requirements. "Truth data", gravity disturbances, are computed on a 5 X 5 km grid on the surface. Dr. Ugincius went on to describe in more detail each of the two models.

Comments:

Dr. Bowin (Woods Hole) - One can get a better model by using smaller masses so as not to destroy long wavelength structure.

Dr. Ugincius - I agree.

Dr. Heller (referring to an earlier statement by Dr. Ugincius) - The TASC data reduction algorithm and the Bell data reduction algorithm are not competing, just independent.

Dr. Ugincius - Only one method may be used at a time, therefore in the future they may be competing.

Mr. Decker - We will use the best algorithm available.

Questions:

Dr. Jekeli - Is there a measure of non-stationarity and non-isotropy for

your model?

Dr. Ugincius - Not now. One can display along-track PSDs or take the average of all along-track PSDs.

Dr. Martin - Are all existing algorithms based on prior knowledge of the gravity model?

Dr. Ugincius - Yes. The two algorithms mentioned this morning are.

Dr. Jordan (Geospace) - It is very common to use prior statistics. If you don't have much data then prior statistics have a big influence. If you are swamped by data then prior statistics have no big effect. Therefore lack of priors are no serious problem to us.

Discussion concerning statistics ensued between Jordan, DeBra, Martin, and Heller.

Post Mission Adjustment of Gravity Gradiometer Data - Dr. Stan Jordan (for Mr. Scott Peacock, Geospace)
Dr. Jordan described a technique for post-mission adjustment of gravity gradiometer data that uses principal component decomposition of the gravity model covariance matrix. This particular form of the Singular Value Decomposition algorithm leads to a very informative transformation of the standard Least-Squares Collocation technique. This transformation allows calculation of the estimates without matrix inversion, and identifies redundancies and near redundancies in the observations. He also presented results from the application of this new technique to gravity gradient analysis as well as suggestions for further development.

Questions:
Dr. DeBra - It is nice to have several methods (for data reduction) but have any comparisons been made?

Dr. Jordan - No, we are waiting for models from NSWC.

Dr. Bose - This a special case of Kalman filtering. Why not use the general case for unbiased states?

Dr. Jordan - We only use biased states.

Mr. Rufty (NSWC) - Is least-squares incorporated?

Dr. Jordan - Yes, it is minimum error variance.

Discussion ensued between Martin, DeBra, and Jordan concerning weights and data reduction.

Frequency Domain Processing of Airborne Gravity Gradiometer Survey Data for Derivation of the Gravity Disturbance Spectrum - Dr. Hutcheson (Bell)
Dr. Hutcheson's presentation was divided into two sections. He presented part I and Mr. Andrew Grierson presented part II. Dr. Hutcheson explained that the measurement of gravity gradients using the Bell Gradiometer in a moving ground vehicle or low altitude aircraft necessitates extraction of a wide bandwidth gravity signature in the presence of instrument and environmental

noise. He described an optimal technique for accomplishing this. The technique incorporates apriori knowledge of these processes which generate the signature and noise but is adaptive to particular mission and instrument characteristics.

Questions:
Dr. De Bra - Why limit the area? (320 km vs 500 km square blocks)

Dr. Hutcheson - We are waiting for a routine to run on the Data General.

Dr. Jekeli - Are those estimates for the total vertical deflection?

Dr. Hutcheson - No, we make a correction for the bias and the trend.

Mr. Vassiliou (Univ. of Calgary) - What about data extrapolation beyond the survey area?

Dr. Hutcheson - It is difficult to do in two dimensions.

Dr. DeBra - Will subsequent 320 km blocks be overlapped?

Dr. Hutcheson - It is a huge issue. We are not concerned with that.

Part II - Mr. Grierson (Bell)

Questions:
Dr. Heller - What kind of bandwidth will the demodulator have?

Mr. Grierson - Depends on actual data. We should try to extend bandwidth out to the signal that you have. If the signal crosses adjacent noise peaks, then determination will be poor.

Dr. DeBra - What is the sensitivity of the weights? How much change can you allow before you need a new set of weights?

Mr. Grierson - I don't know. We need to do examples for various bandwidths.

a. On the Problem of Astrogeodetic-Gradiometric Vertical Deflection Determination in Mountainous Terrain
b. A High Accuracy Astrogeodetic-Inertial Data Base for Tests of the Bell Gravity Gradiometer - Dr. H. Baussus von Luetzow (Army ETL)
Dr. von Luetzow discussed topics a and b pointing out problems to be solved and other areas of concern to researchers in the field.

Analysis of the High Frequency Spectrum of the Anomalous Potential - Mr. Anthony Vassiliou (Univ. of Calgary)
Mr. Vassiliou emphasized that the knowledge of the high frequency spectrum of the anomalous gravity potential is important for the development of data processing techniques in airborne gradiometry. This spectral information can be obtained by analyzing dense gravity data by FFT methods. An attempt has been made to use available data files in Canada for this purpose. He explained that the data considered consisted of a rather uniform set of (5' X 5') mean anomalies in most of the continental areas and four sets in specific areas with an average data spacing of about 1 km. The analysis showed that the

gravity spectrum has to be resolved to about degree and order 7000, i.e. to a point spacing of about 3 km, to resolve the gravity anomalies to the one mgal level. This means that a similar data spacing would be required for airborne gradiometry in order to get an equivalent resolution. The derived spectrum was then used to determine suitable degree variance models and covariance functions for airborne gradiometry. Results of mean 5' X 5' gravity anomalies covering the non-mountainous areas of Canada indicate that the degree variances of the anomalous potential decay like $^{-3.6}$ and not as $^{-3}$ as Kaula's rule implies. This would mean that a second-order Gauss-Markov model agrees better with the results from this analysis than a third-order model.

Questions:
Mr. Zorn - How do results relate to gravity gradients.

Mr. Vassiliou - One can get analytical expressions for gradients in all models.

Comment, Dr. Baussus von Leutzow (Army ETL) - Drawbacks with the second order Gauss-Markov model can be overcome with Taylor series and finite differences.

A discussion among Baussus, Bose, DeBra, Heller, and Hutcheson followed concerning data point spacing along the survey track at other than grid intersections.

Wednesday Morning Session

<u>Two-Dimensional Karhunen-Loeve Smoothing of Gravity Gradiometer Surveys</u> - Dr. Sam Bose (Applied Sciences Analytics Inc)
Dr. Bose opened with a review of the usual assumptions made when processing gravity gradients. Moving base gravity gradiometry (MBGG) offers a much higher resolution compared to conventional gravity surveys. The increased speed and resolution possible with MBGG comes with a price tag; that of dealing with enormous volumes of data in the five independent gradient tensor components of the gravity gradiometer. Gravity gradients are not fundamentally different from gravity measurements yet their processing by means of conventional techniques is both inappropriate and inadequate. The simplistic approach of integrating a single gradient component along the track of the moving platform to derive a gravity profile ignores the information contained in the cross-track and gradients. Dr. Bose presented a two-dimensional signal processing algorithm to process all the gradiometer data simultaneously. The measurement data can be collected at any altitude on or above the surface of the earth in a planar gridded form. The method differs from conventional least squares techniques in that it accomodates statistical models for both the gravity signal and measurement errors. The gravity signal model is derived from the physical theory of geodesy and is based on the concept of modeling the unknown mass distribution below the survey region as multiple two-dimensional white noise layers representing the vertical derivative of the disturbance potential to any order. Such a model requires no restrictions of causality, stationarity, or isotropy. The problem of simultaneous smoothing of all the gradient measurements from all survey traverses in the region is solved by representing the disturbance potential solution as a Karhunen-Loeve expansion. Estimating the gravity field simply reduces to estimating the Karhunen-Loeve coefficients which are uncorrelated and converging. The implementation of the algorithm requires no matrix inversions and can handle

large amounts of data in a computationally efficient manner.

Questions:
Mr. Benson (Dynamics Research) - What is lost by truncating the series?

Dr. Bose - Truncation is done by setting M = K (Nyquist limit).

Mr. Benson - Does the method have to be modified for real time estimation?

Dr. Bose - This is not a real time estimation technique.

Deterministic and Stocastic Representations of Gravity Gradients Using Spherical Harmonics - Mr. M. May (NADC)
Mr. May presented expressions for the anomalous gravity gradient maps in terms of spherical harmonics. Comparisons among different coefficient sets are quantified. A stochastic gravity field spherical model is fit and extrapolated to the data. From this the corresponding parameters of the planar field model are derived.

Questions:
Dr. Jekeli - Why are there no gradients (on your map) in the Atlantic?

Mr. May - The contour interval is 5 E.

Dr. Jekeli - Is the expansion to degree 180?

Mr. May - Yes

Lt Fundak - What is the tactical filter?

Mr. May - The filter used in submarines for real-time applications.

Mr. Molny - What is the sensitivity of the tactical filter?

Mr. May - It is sensitive to low frequencies.

Mr. Zorn - Is the equivalence between MAG and STAG exact for the planar case?

Mr. May - Yes.

Review of Superconducting Accelerometer and Gravity Gradiometer at the University of Maryland - Dr. Ho Jung Paik (Univ. of Maryland)
A sensitivity goal of 3 X 10^4 E $Hz^{-1/2}$ has been defined for the Gravity Gradiometer Mission (GGM) at NASA. Dr. Paik and his associates are constructing a three axis superconducting gradiometer, which will be interfaced with a new six axis superconducting accelerometer for a flight on the Space Shuttle. The immediate sensitivity goal is 2 X 10 E $Hz^{-1/2}$, which will be increased by another order of magnitude for the mission. Experiences obtained with the prototype single-axis instrument as well as innovations in superconducting technology have been incorporated in the design of the advanced model of the gradiometer. The six-axis accelerometer will measure three components of linear acceleration and three components of angular acceleration simultaneously by monitoring the motions of a single magnetically levitated proof mass. The outputs of this accelerometer will be used to isolate the platform from vibration and to compensate for dynamically induced errors from the gradient measurement.

Dr. Paik discussed the principles and designs of these instruments and their development schedules. He also discussed possible applications of such sensitive instruments for fundamental physics experiments, terrestrial gravity surveys, and inertial navigation surveys.

Questions:
Dr. Martin - How realistic is your work schedule, especially the flight in 1989?

Dr. Paik - If there are no restrictions on funding and hiring - yes it is realistic. But currently, funding is restricted and personnel is limited.

Dr. Martin - Are there technological problems?

Dr. Paik - Depends on the goals for the gradiometer. The 6 axis accelerometer is new and higher risk.

Dr. Ugincius - What is the most sensitive test for the inverse square law?

Dr. Paik - Depends on the range of resolution. At a few kilometers we don't have good data.

Basic Concepts in Real-Time Processing of Gravity Gradiometer Data - Dr. William Chairetakis (Sperry)
Dr. Chairetakis discussed techniques for obtaining, in real-time, anomalous gravity gradients in the local level (North, East, Down) frame from a gradiometer consisting of three carouselled Bell Gravity Gradiometer Instruments. He first described a technique for estimation and direct compensation of the effects of low frequency instrument errors on the gradients. He then discussed the technique of pair-processing which allows the real-time estimation of the complete set of gradients from only two instruments. He further presented the integration of these two techniques into a real-time algorithm; this algorithm first obtains three sets of pair-gradients free of low frequency instrument errors and subsequently weights these continuously (according to most recent estimates of the quality of instrument outputs) to obtain a final estimate of the local level gradients. He claims this process provides the best real-time measurements possible without the aid of information external to the system.

Inferring Gradiometer Environmental Sensitivity From Long Term Test Data - Mr. Donald Benson (Dynamics Research Corporation)
Since Mr. Benson did not offer a written abstract and his paper was classified SECRET, no notes were taken on his presentation.

Techniques for Using Multipole Distributions in GGSS Stage II Data Processing - Mr. Alan Rufty (NSWC)
Mr. Rufty presented an extension of his previous work on the approximation of the Earth's gravity field by point masses. The treatment of point multipole distributions is accomodated within the point mass formalism previously developed. In this connection he also presented the accuracy of global combined point mass/dipole nonlinear least squares fits developed to model tesseral gravity fields. Mr. Rufty described an extension of the formalism that develops a candidate technique for the operational data reduction approach needed in support of the Gravity Gradiometer Survey System.

Questions:
Dr. Bose - Will there be conversion problems?

Mr. Rufty - You have to choose spacing carefully to be consistent with data processing.

Dr. Goldstein - How time consuming is the implementation?

Mr. Rufty - Fairly operationally efficient. We are inverting small matrices.

Lt Fundak - What is the difference between high pass/low pass vs bandpass filters?

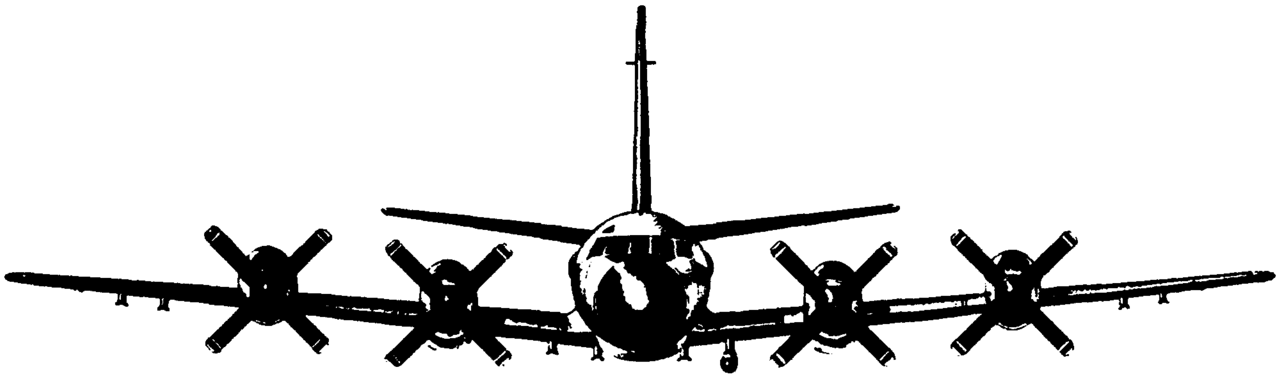
Mr. Rufty - None.

Closing - Dr. Martin called upon Dr. Dan DeBra of Stanford University to offer closing remarks. Dr. DeBra stated that he was glad to see such low errors in the gravity gradiometer instrument (GGI). But he also pointed out that we shouldn't become overly confident. There is a need for cross checking using LaPlace transforms and carouselling. He suggested that if there is another generation of GGIs that another sensor be added to give a higher confidence level. Dr. Debra also noted that the principle discussion at this year's conference revolved around data fitting. He considers this a very relevant issue and regards Dr. Peter Ugincius' work as most important in the field. Dr. DeBra mentioned that he is concerned with what he considers the over-emphasis on statistical modeling. He pointed out that we shouldn't be diverted by the amount of importance placed on statistics. He emphasized the need for multiple methods for fitting the data and that we need independent checks for consistancy. Dr. DeBra remarked that models are good, but not guarranteed. Dr. DeBra made a quick reference to data reduction and survey techniques. He posed the question of whether or not we need to repeat the track at the end of the survey. He stated that this might be a good way to avoid losing a chunk of data on a day to day basis. Other points addressed were 1) data processing; should we use all the data or not? 2) practical aspects of the need for aircraft requirements; we need to distinguish between the control of the aircraft and control of the sensors. In general Dr. DeBra considered the program to be progressing well and making strides in the right directions.

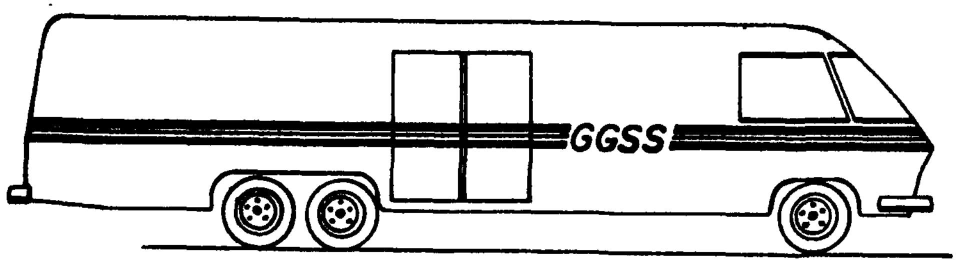
1985 Conference Attendees

Organization	Name
AFGL	Dick Borgeson Don Eckhardt Terry Fundak Chris Jekeli Tom Rooney Donna Warner Rob Goldsborough
AFIS	J. Edward Jones
Applied Sciences Analytics	Sam Bose
Army - ETL	H. Baussus von Luetzow Eugene Rose
Bell Aerospace Textron	Clive Affleck John Hutcheson Al Jircitano Ernest Metzger Andrew Grierson
DMA	Erich Rutscheidt Charlie Martin Randy Smith
DMAAC/STT	B. Louis Decker John Graham Melvin Shultz
DMAHTC/DET4	Maj Brian Mertz
DMAHTC/GSS	Jerome Kurkowski Ludvik Pfeifer
DMAHTC/GST	Benny Klock Archie Carlson
DMAHTC/STT	Robert Gouker
Dynamics Research	Don Benson Alan Zorn
Geodynamics	Chris Harrison
Geo-Sensors	Jeffery Zeamer
Geospace	Larry Bradley Stan Jordan
Honeywell	Michael Hadfield

Organization	Name
Johns Hopkins	Jose Latimer Jonathan Howland Paul Zucker
Mobil Oil	Perry Parks
NADC	John De Matteo Marvin May
NRL	John Brozena
NASA	Werner D. Kahn
NSWC	Peter Ugincius Alan Rufty Ted Sims
Sperry	William Chairetakis Rudy List Marvin Molny Alexander Chwick
SSPO	Bernard Epstein Bernard Wolfson Jerome Katz
Stanford	Dan DeBra
TASC	Warren Heller Jake Goldstein Ellen Meadors
University of Calgary	Anthony Vassiliou
University of Maryland	Ho Jung Paik
US Geological Survey	William Hanna
Woods Hole	Carl Bowin



GRAVITY GRADIOMETER SURVEY SYSTEM (GGSS) PROGRAM



GGSS

1984 IN REVIEW

▲ PHASE II TEST AREA CHOSEN	MAR 84
▲ P-3A 151384 AUTHORIZATION	JUN 84
▲ P-3A MODIFICATION PROGRAM	JUL 84
▲ GPS NAVAID RECEIVED	DEC 84
▲ 1ST GGI UP AND RUNNING	DEC 84
▲ P-3A 151384 TRANSFERRED TO DMA	JAN 85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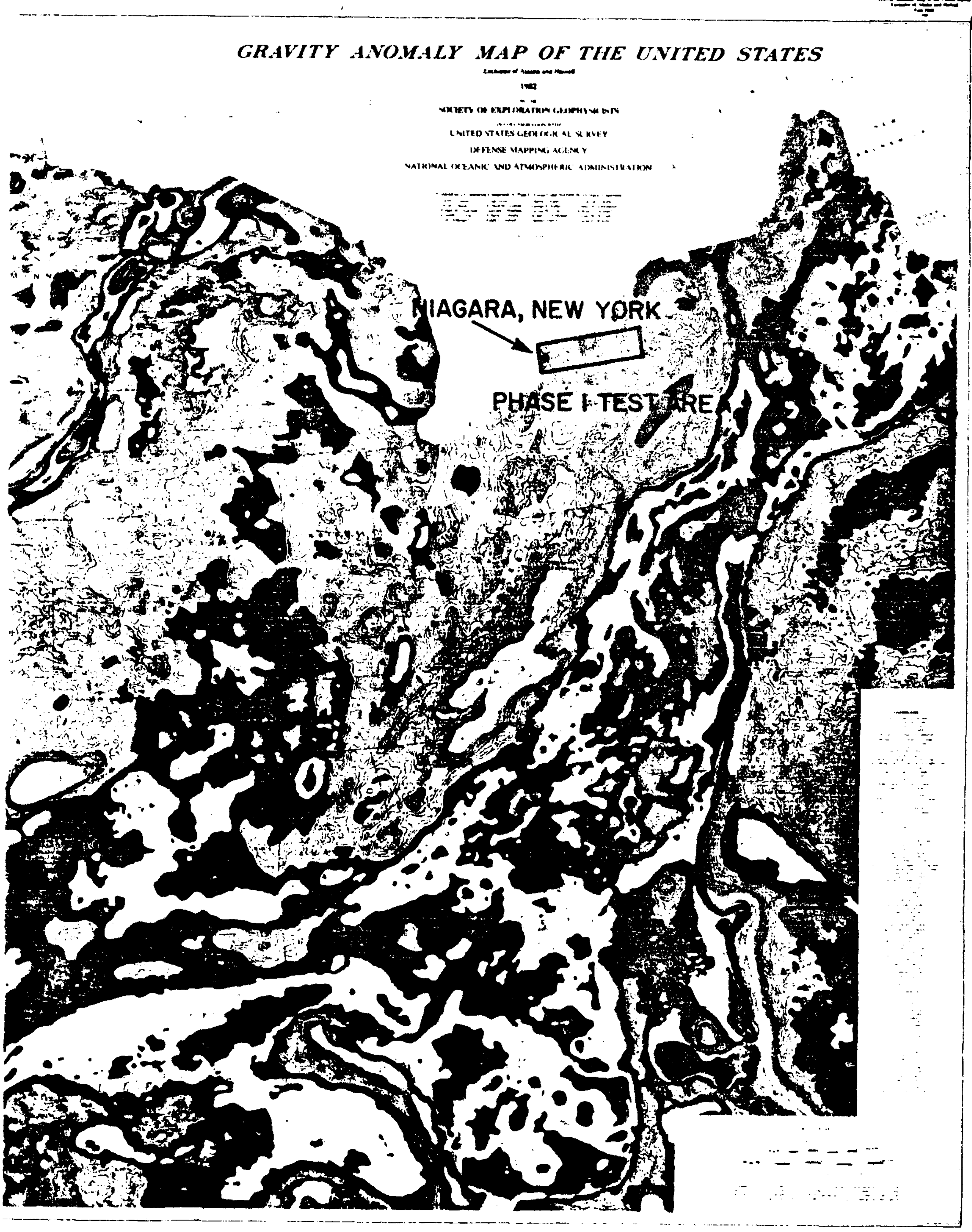
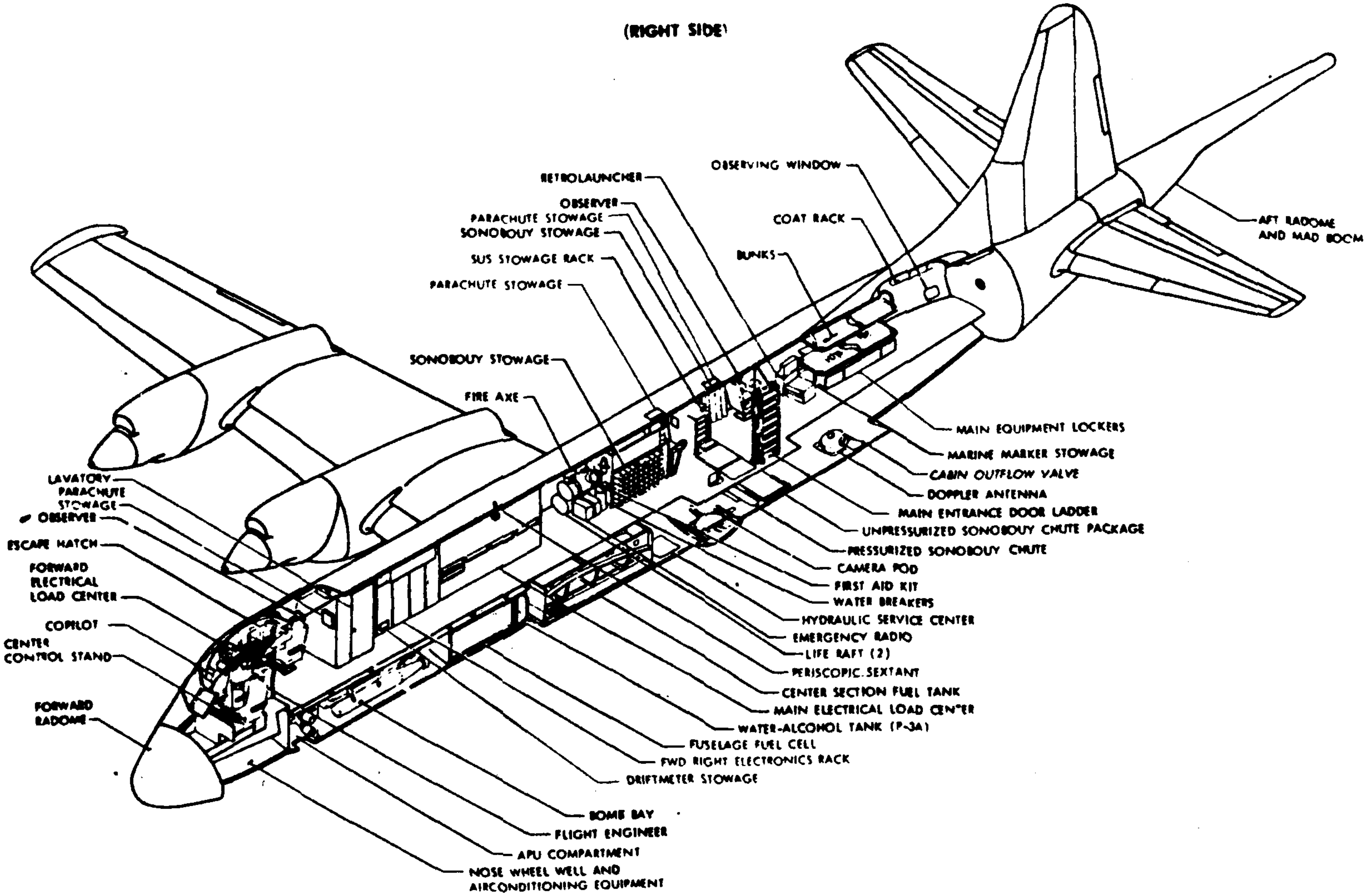
PHASE


GRAVITY ANOMALY MAP OF THE UNITED STATES
SOCIETY OF EXPLORATION GEOPHYSICISTS
UNITED STATES GEOLOGICAL SURVEY
DEFENSE MAPPING AGENCY
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NIAGARA, NEW YORK
PHASE I TEST ARE

GENERAL ARRANGEMENT DIAGRAM - DIFAR AIRCRAFT

(RIGHT SIDE)



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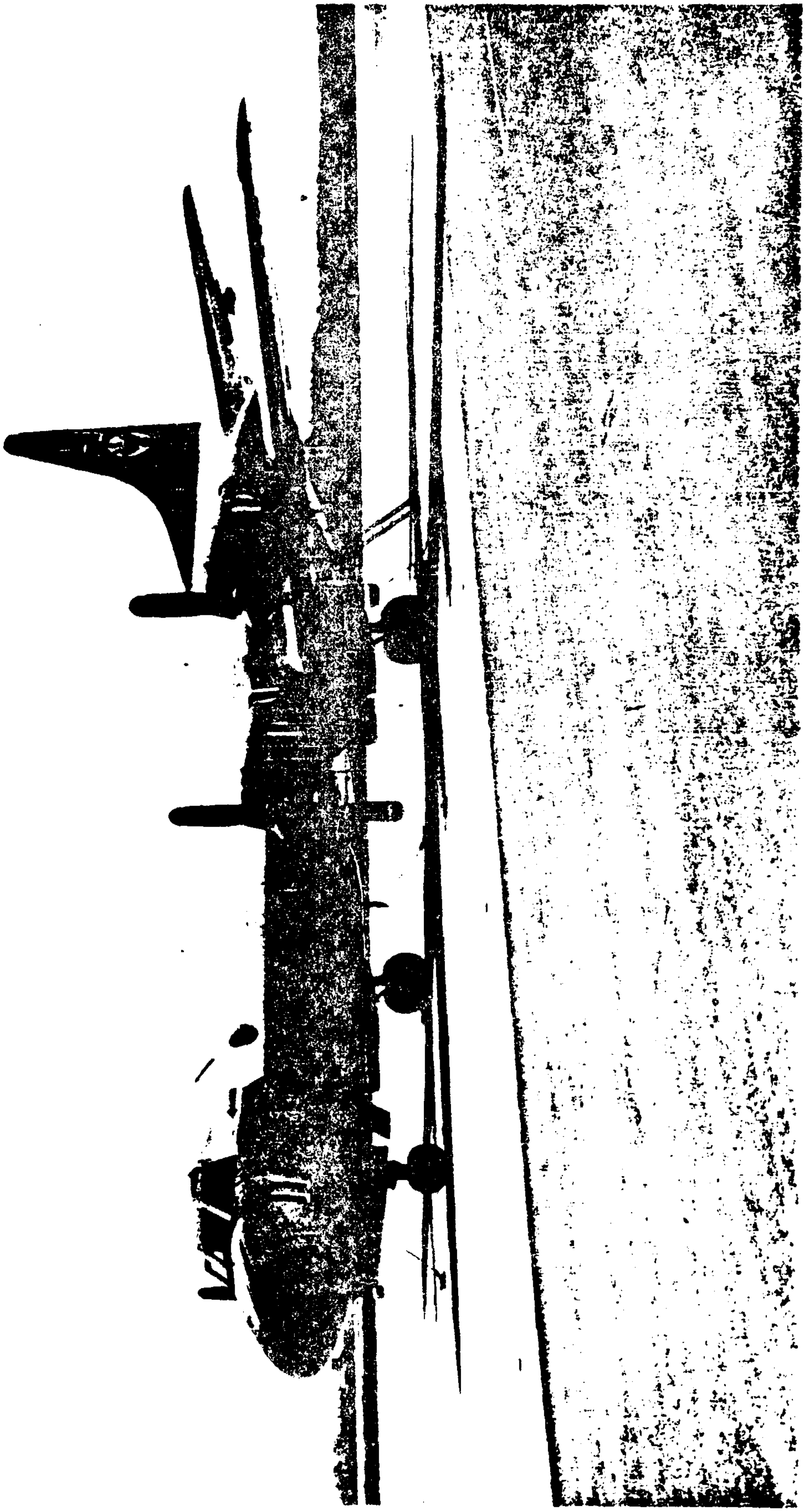
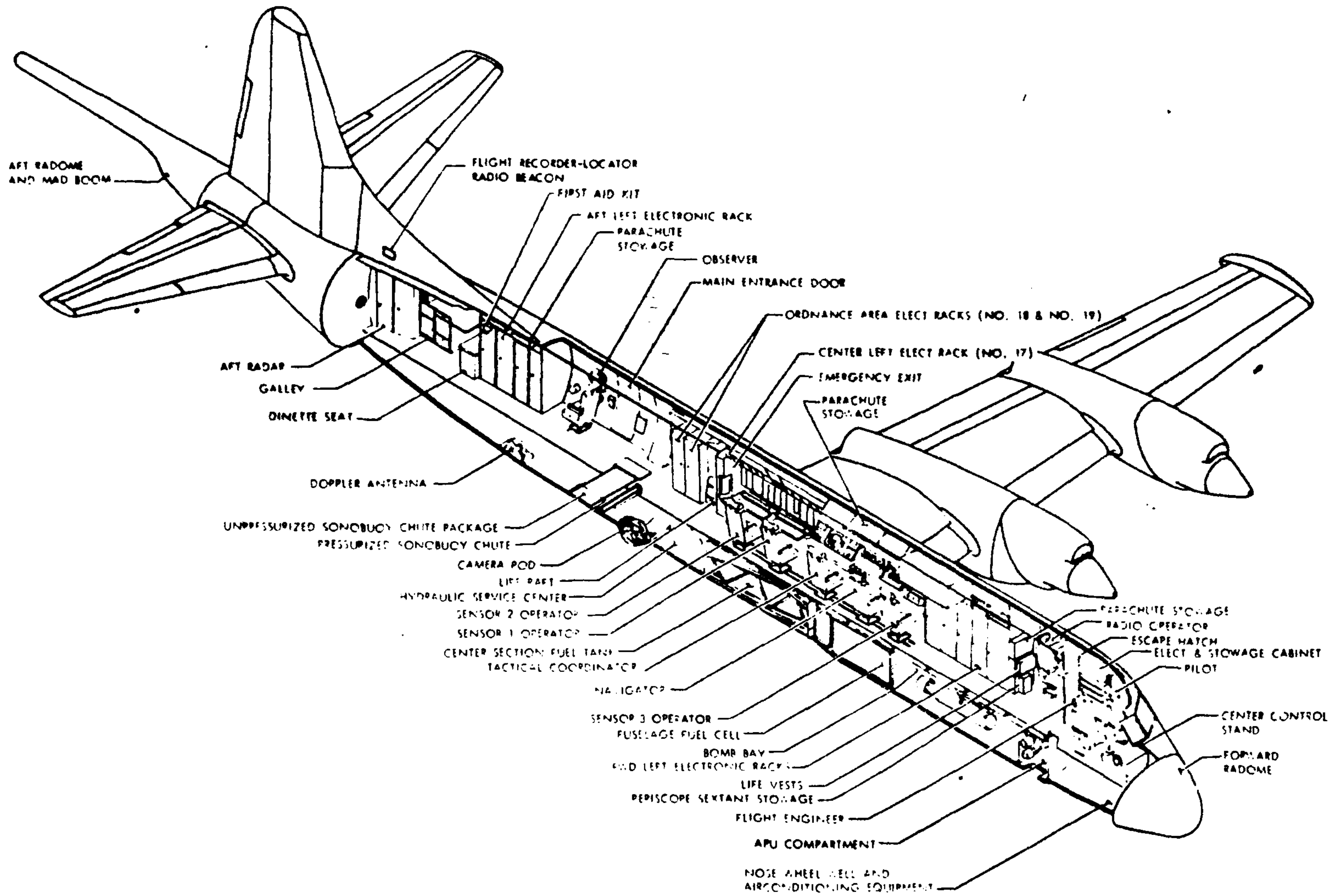
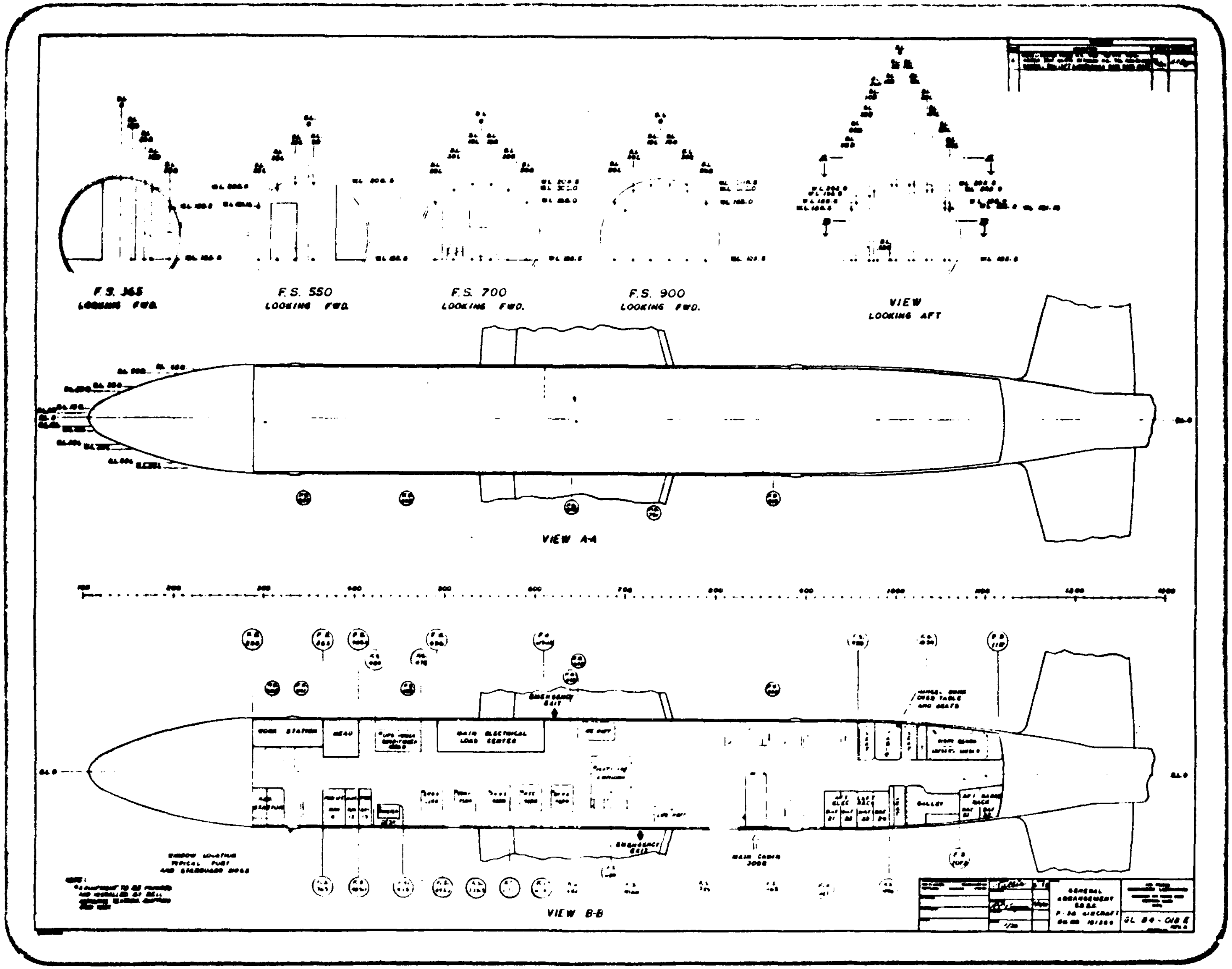


GENERAL ARRANGEMENT DIAGRAM - DIFAR AIRCRAFT

(LEFT SIDE)




F.S. 365
LOOKING FWD.
F.S. 550
LOOKING FWD.
F.S. 700
LOOKING FWD.
F.S. 900
LOOKING FWD.
VIEW
LOOKING AFT
VIEW A-A
WORK STATION
HEAD
MAIN ELECTRICAL LOAD CENTER
EMERGENCY EXIT
GALLEY
MAIN CABIN DOOR
VIEW B-B
GENERAL ARRANGEMENT

GGSS

1985 AND BEYOND

△ SYSTEM INTEGRATION	APR 85
△ LAB TESTS (3MO)	JUL 85
△ GO AHEAD FOR 2ND GGSS SYSTEM	MAR 86
△ PHASE I LAND VEHICLE TESTS	MAR 86
△ P-3 MODIFICATION COMPLETE	APR 86
△ AIRCRAFT DELIVERED TO BELL	APR 86

GGSS

<u>1985 AND BEYOND</u>

△ PHASE II LAND TESTS	APR 86
△ PHASE I AIRCRAFT TESTS (1MO)	AUG 86
△ PHASE II AIRCRAFT TESTS (2MO)	SEP 86
△ GGSS NO. I DELIVERY	NOV 86
△ GGSS NO. II DELIVERY	FEB 88

MOVING BASE GRAVITY GRADIOMETER REVIEW

Book 1

Review of GSS OSDP Program Activity for 1984

Air Force Academy

Report No. 6501-927078 • FEBRUARY 12 - 13, 1985

Bell Aerospace TEXTRON

POST OFFICE BOX ONE • BUFFALO, NEW YORK 14240

SUMMARY DESCRIPTION OF GRAVITY SENSOR SYSTEM
GSS OSDP

1 GRAVITY SENSOR PLATFORM (GSP)

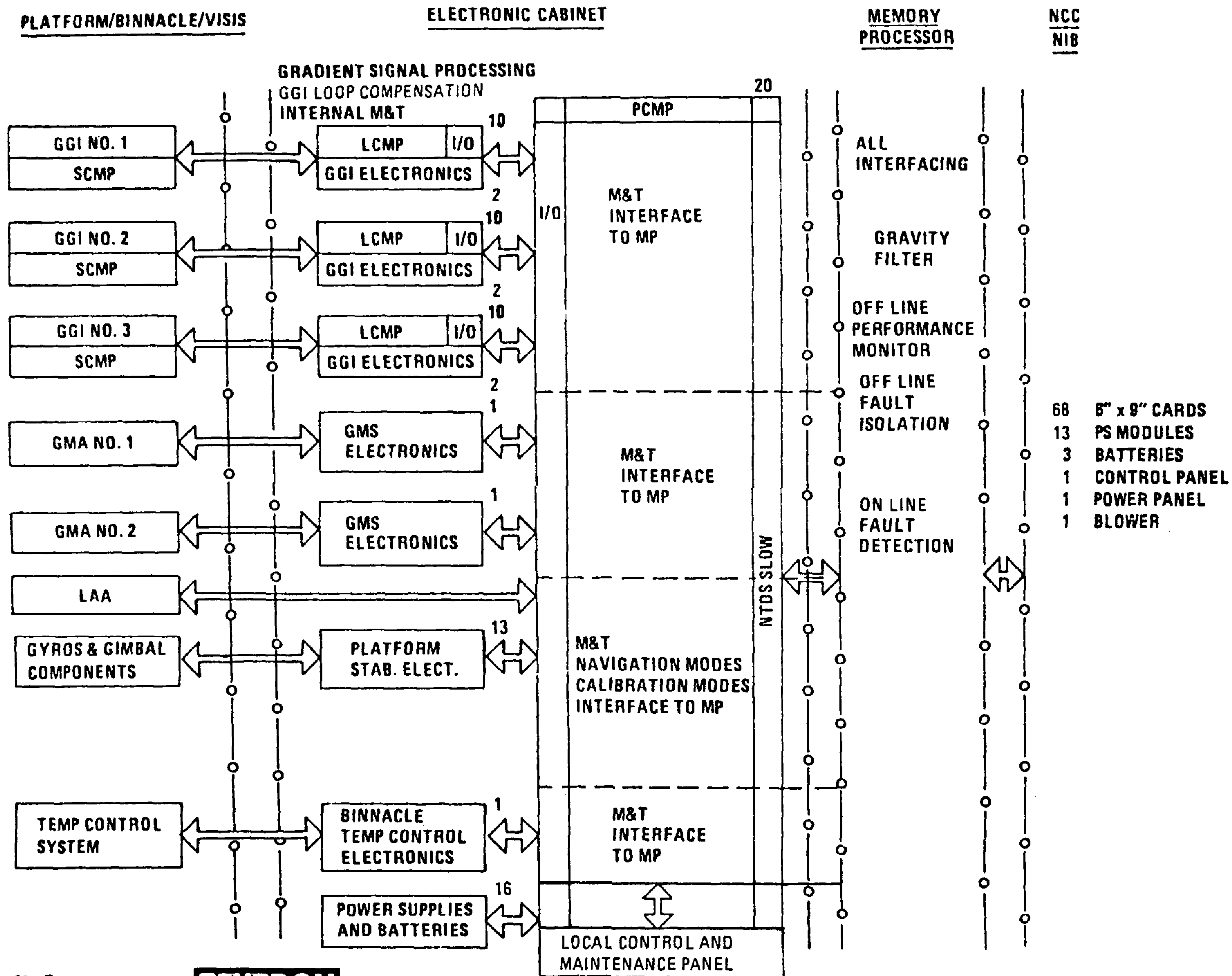
- 3 GRAVITY GRADIOMETER INSTRUMENTS (GGIs)
- 2 GRAVITY MODULE ASSEMBLIES (GMAs)
- 2 DRY TUNED GYROS (LITTON)
- 1 LEVELING ACCELEROMETER ASSEMBLY (LAA)

1 GSS ELECTRONICS CABINET (GEC)

- 68 6 IN. x 9 IN. ELECTRONIC BOARDS
- 13 POWER SUPPLY ASSEMBLIES
- 3 BATTERIES
- 1 BLOWER
- 1 LOCAL DISPLAY AND CONTROL PANEL

1 MEMORY PROCESSOR (MP)

GSS OSDP FUNCTIONAL BLOCK DIAGRAM



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LOOP CLOSURE MICROPROCESSOR (LCMP) FUNCTIONS

- 3 AUTOMATIC, ON LINE SCALE FACTOR BALANCE LOOPS
- 1 AUTOMATIC, ON LINE AXIAL ALIGNMENT LOOP
- DEMODULATES AND FILTERS GRAVITY GRADIENT SIGNALS
- GENERATES AUTOMATIC FAULT DETECTION AND ISOLATION SIGNALS
- FOUR FIXED LEVEL EVEN ORDER ERROR COEFFICIENT COMPENSATION SIGNALS, CHANGEABLE ON COMMAND

PLATFORM CONTROL MICROPROCESSOR (PCMP) FUNCTIONS

- CONTROLS GSP
  - 5 OPERATING MODES
  - 5 CALIBRATION MODES
- CONTROLS INTERFACE
  - TO AND FROM MEMORY PROCESSOR VIA NTDS
  - TO AND FROM MAINTENANCE AND CONTROL PANEL
  - TO AND FROM OTHER GSS EQUIPMENT
- CONTROLS START UP SEQUENCE
  - OPERATIONAL
  - DIAGNOSTIC ON COMMAND FROM MP OR MAINTENANCE PANEL

MEMORY PROCESSOR (MP) ON LINE FUNCTIONS

- AUTOMATIC FAULT DETECTION – EVALUATES SIGNALS FOR FAULT CONDITION
- COMPENSATES GGI SIGNALS FOR BIAS, SCALE FACTOR, MISALIGNMENT, SENSITIVITY
- COMPENSATES GMAs FOR BIAS, SCALE FACTOR, MISALIGNMENT
- FILTERS ENVIRONMENTAL DATA-MATCHED TO GGI BUTTERWORTH
- DERIVES GRAVITY DISTURBANCE VECTOR FROM COMPENSATED GGI AND GMA SIGN
- TRANSMITS INFORMATION

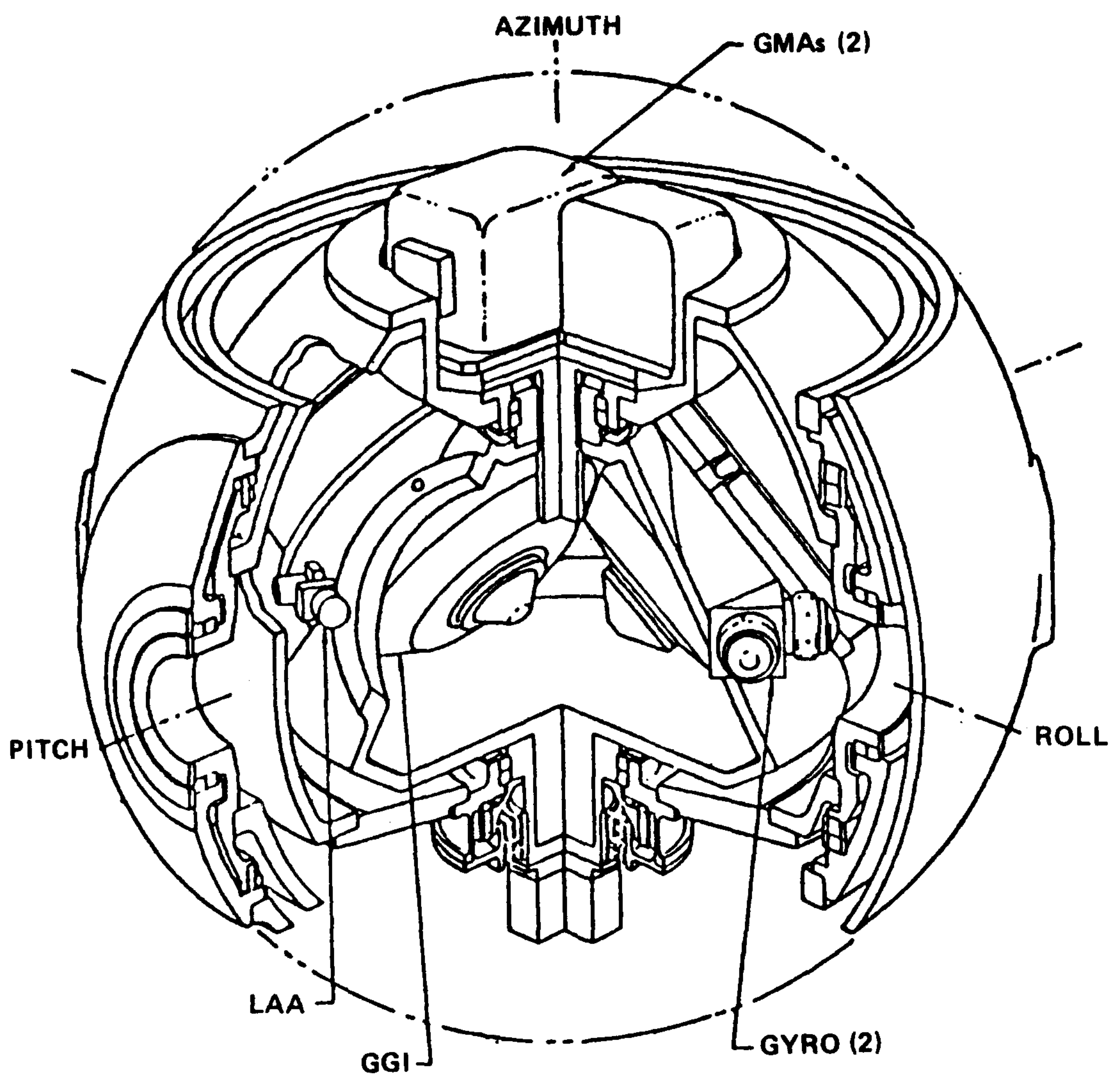
  TO AND FROM NCC AND NIB

  TO AND FROM PCMP
- ON LINE GGI AND GMA FAILURE DETECTION BY PERFORMANCE MONITOR

MEMORY PROCESSOR (MP) – OFFLINE FUNCTIONS

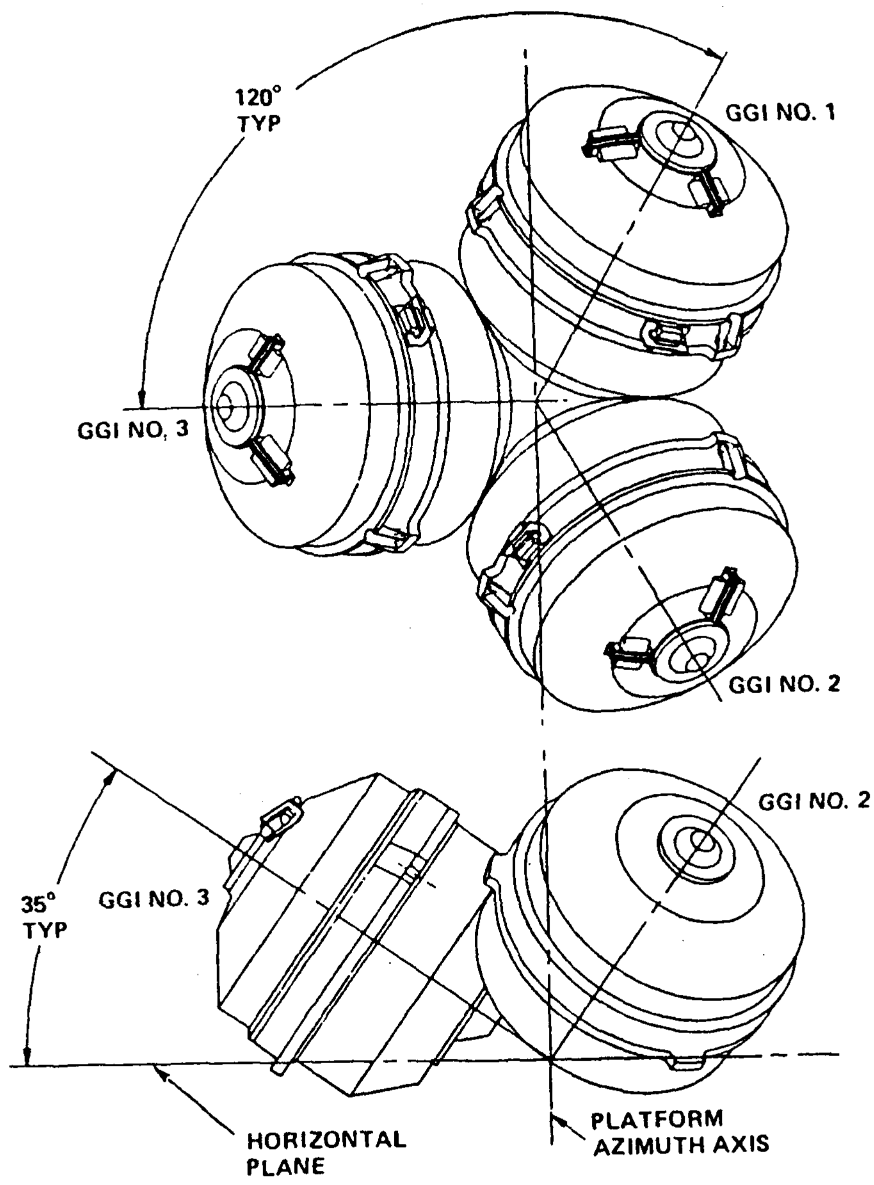
- AUTOMATIC FAULT ISOLATION
  - DIRECTS AUTOMATIC DIAGNOSTIC TEST SEQUENCE
  - EVALUATES OUTPUT SIGNALS FROM DIAGNOSTIC TEST SEQUENCE FOR PASS-FAILURE CRITERIA
  - BASED ON EVALUATION OF GROUP OR GROUPS OF TEST SIGNALS DETERMINES MOST LIKELY FAILED MODULES IN ORDER OF PROBABILITY
- *CALIBRATION*
  - DIRECTS SELECTED CALIBRATION SEQUENCE
  - EVALUATES CALIBRATION DATA AND DERIVES CALIBRATION CONSTANTS
  - STORES CALIBRATION CONSTANTS ON RECOVERY TAPE AND TRANSMITS TO PCMP
- PERFORMANCE MONITOR
  - DERIVE SELECTED PSDs, DRIFTS, BIASES, DEVIATIONS, ETC.

PLATFORM CUTAWAY DRAWING



GSS ADM Platform Showing Location of GMAs

ORIENTATION OF GGIs



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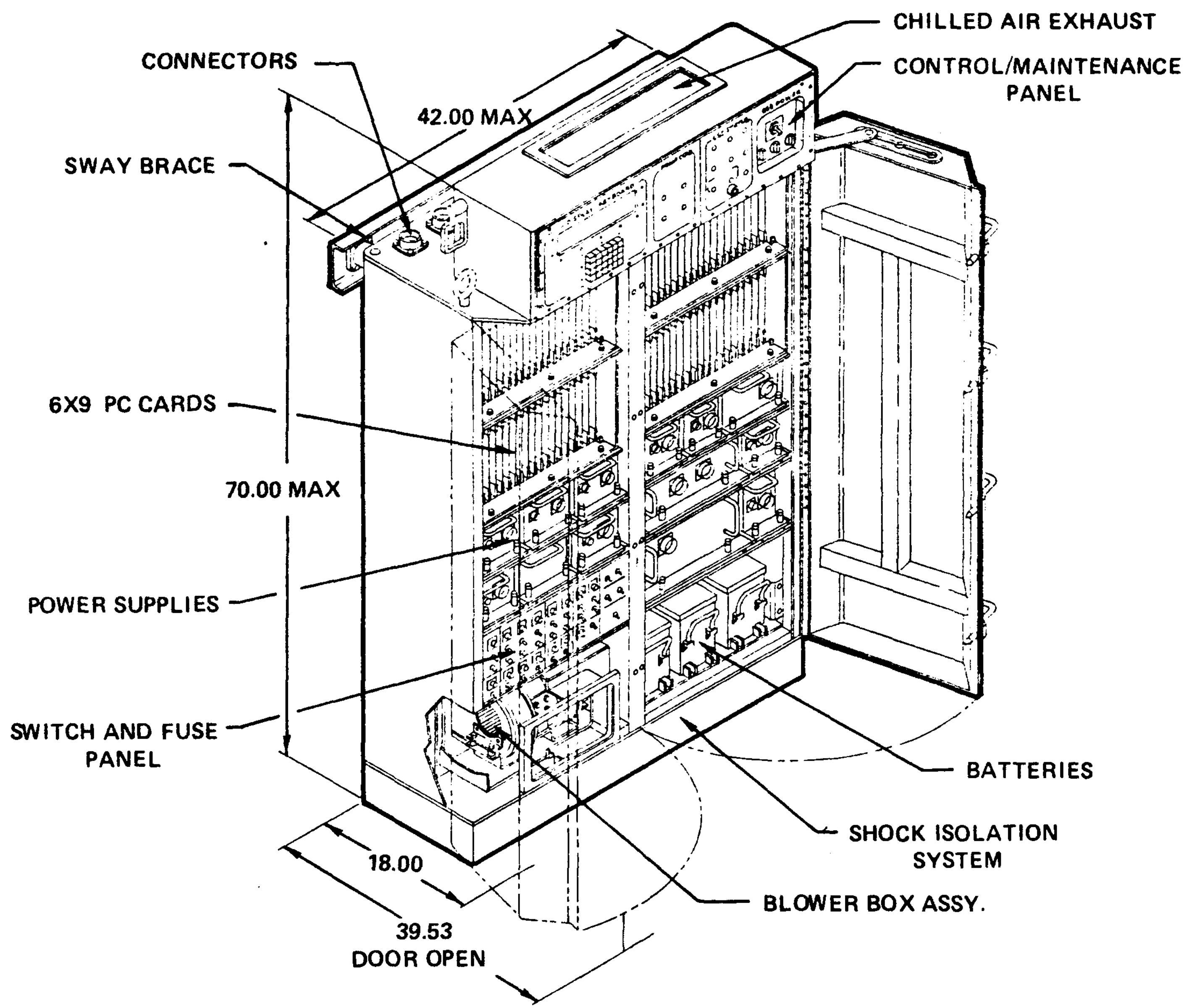
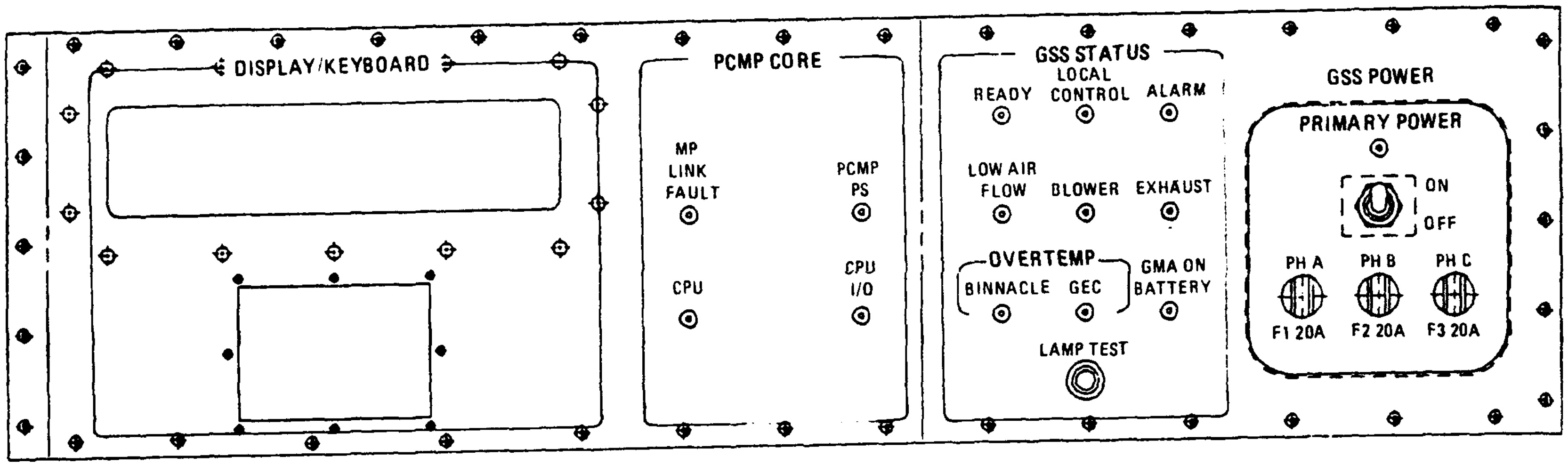
GSS ELECTRONICS CABINET



CONTROL/MAINTENANCE PANEL



GSS OSDP KEY MILESTONES SINCE 1984 REVIEW

- GSS ADM NO. 1 CONTINUES TO OPERATE WELL ON USNS VANGUARD
- GSS ADM NO. 2 USED AT BELL TO VERIFY MODS FOR OSDP
- BREAD BOARD OSDP GGIs SUCCESSFULLY TESTED ON USNS VANGUARD
- SIGNIFICANT ERROR MECHANISM CONTRIBUTING TO GGI ACCELERATION SENSITIVITY IDENTIFIED
- REPLACEABLE GGI SLIP RING ASSEMBLY WITH POTENTIAL OF 23,000 HR MAINTENANCE FREE OPERATION LOOKS PROMISING
- GGI SHOCK TESTED
- HARDWARE DESIGN 95% COMPLETE
- COMPREHENSIVE AUTOMATIC FAULT ISOLATION SYSTEM TO MODULE LEVEL DESIGNED
- SOFTWARE/FIRMWARE PROGRAMS SPECIFIED AND IN DETAIL DESIGN
- PARTIAL INTEGRATION ON MODULE LEVEL INITIATED
- DEDICATED GSS MANUFACTURING AND TEST FACILITY PUT INTO PLACE

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GSS ADM No. 1 and 2 Experience

GSS ADM NO. 1 ON NTV

1984 ACTIVITIES

- REPLACED ALL GEC BLOWER FANS WITH HIGHER RELIABILITY MODEL
- IDENTIFIED CAUSE OF AZIMUTH GIMBAL STICTION PROBLEM AS OXIDATION OF MIL-L-6085 LUBRICANT IN THE LOWER AZIMUTH BEARING
- EVALUATION OF BRAYCO 8152 LUBRICANT, SELECTED FOR OSDP BEARINGS, STARTED BY REPLACING LOWER AZIMUTH GIMBAL BEARING
- EVALUATED ADM GGI COMPLEMENTED WITH LOW PENDULOSITY ACCELEROMETERS
- EVALUATED TWO OSDP BREADBOARD GGIs
- ACQUIRED DATA FOR VERIFICATION OF PLANNED OSDP SELF GRADIENT CALIBRATION APPROACH
- DETERMINED THAT GGI ACCELERATION SENSITIVE ERROR COEFFICIENTS SETTING TECHNIQUE REQUIRED REVISION

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GSS ADM NO. 2

PRIME OBJECTIVE

SUPPORT THE DESIGN OF THE OSDP SYSTEM

1984 ACTIVITIES

- DETECTED AND CORRECTED ROLL AXIS STICTION PROBLEM
- ELIMINATED BINNACLE BUFFER AMPLIFIERS
- CHECKED THAT ALL GIMBAL RESONANT FREQUENCIES >200 Hz
- CONDUCTED 50° INCLINATION TEST
- TESTED WIRING CHANGES TO ACHIEVE INDEPENDENT GGI OPERATION
- CONDUCTED FUNCTIONAL AND LIMITED PERFORMANCE TESTING OF GMA CHANNEL
- CHECKED OUT ALL INERTIAL COMPONENT OSDP CALIBRATION ALGORITHMS
  - GYRO
  - LAA
  - GMA
  - GGI
- CHECKED OUT OSDP PLATFORM CONTROL ALGORITHMS
- CHECKED OUT COMPATABILITY OF OSDP BREADBOARD GGIs PRIOR TO INSTALLATION ON NTV
- INTEGRATED OSDP BREADBOARD PLATFORM CONTROL ELECTRONICS WITH THE PLATFORM
- CONDUCTED FORMAL PLATFORM SERVO TESTS
- DEMONSTRATED OSDP START—UP AT SEA CAPABILITY

OSDP GGI PROGRESS

- GGI SLIP RING ASSEMBLY
- GGI SHOCK TEST
- ERROR COEFFICIENT CALIBRATION

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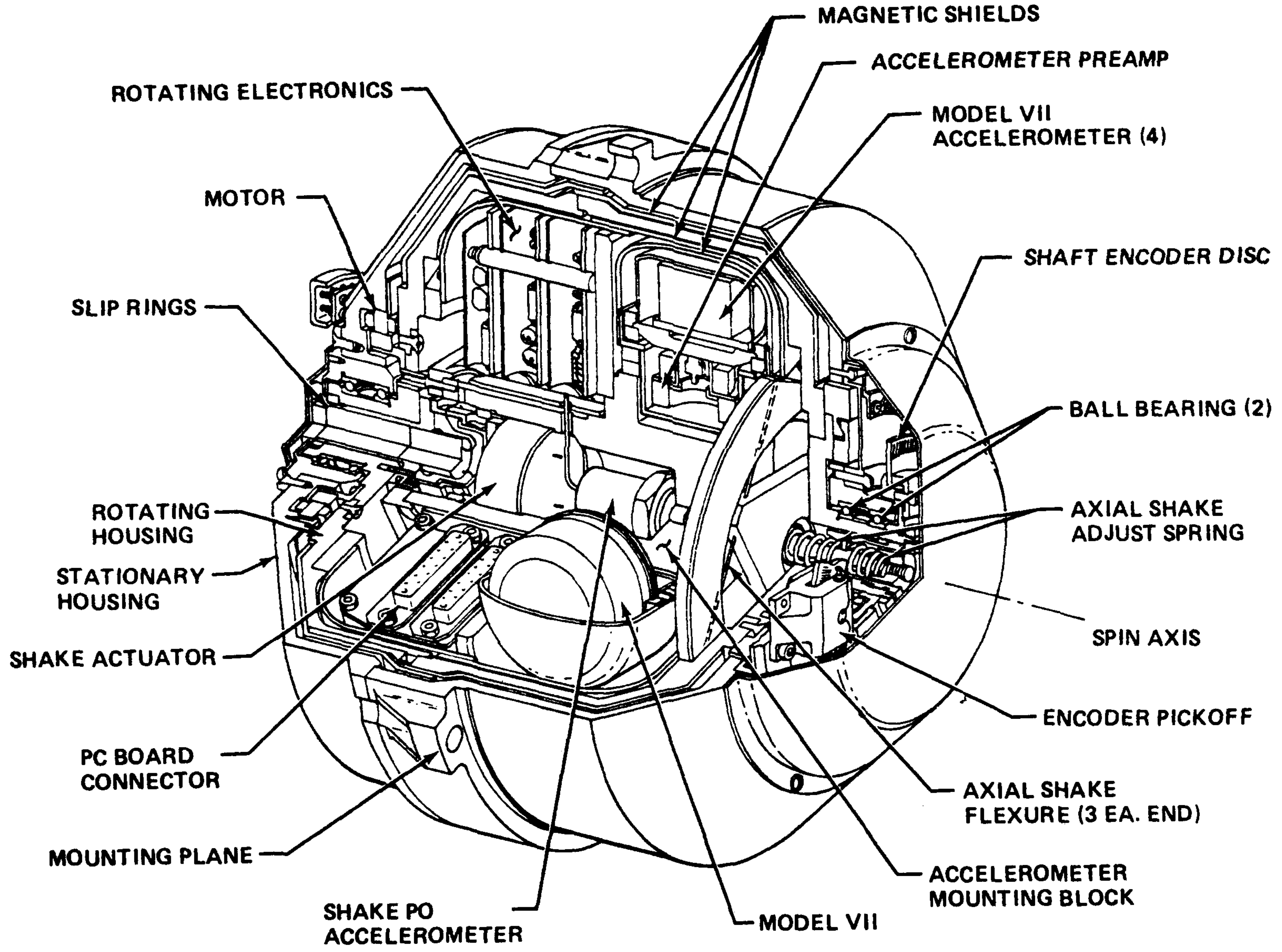
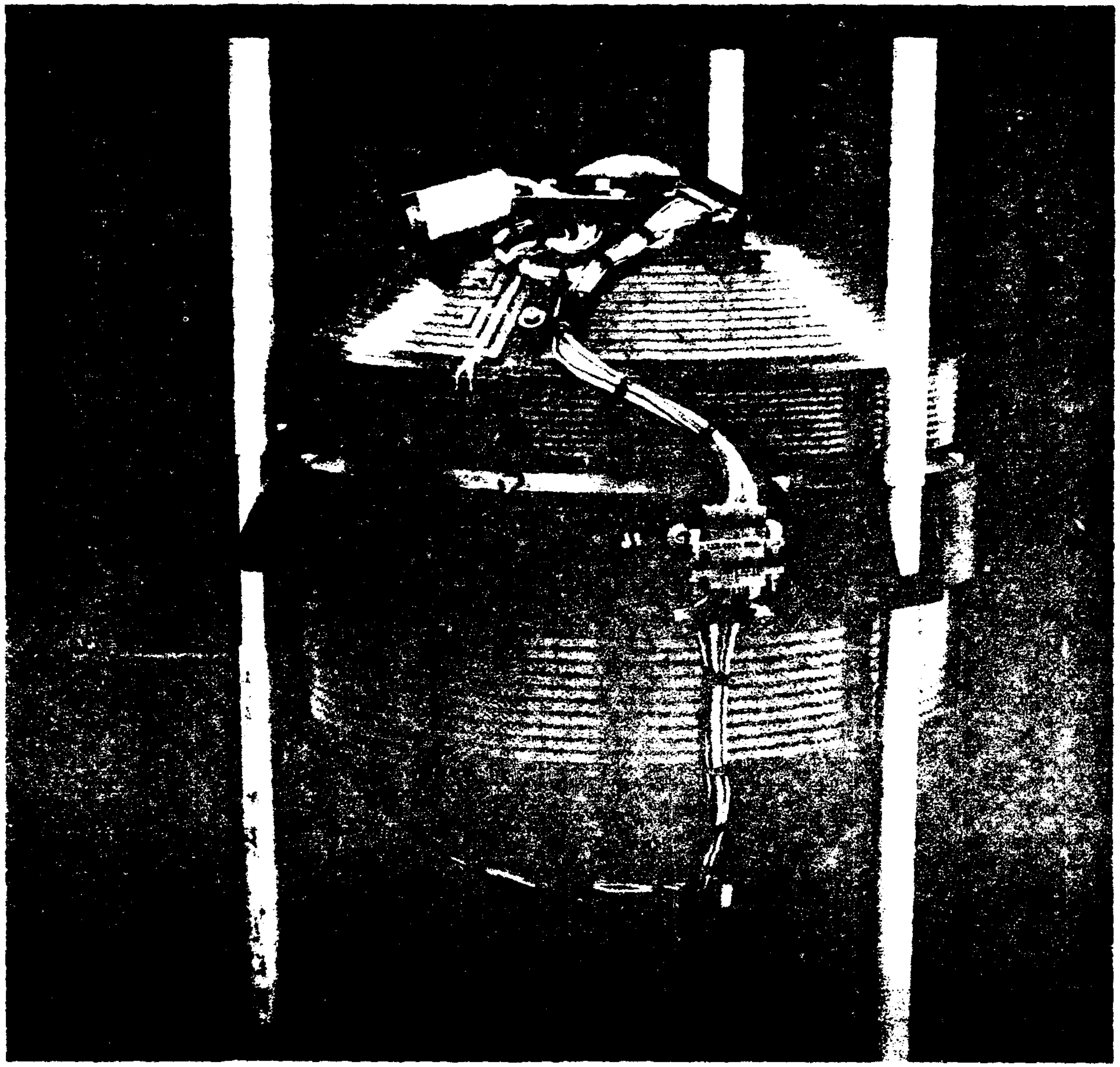
GRAVITY GRADIOMETER INSTRUMENT



ADM GGI



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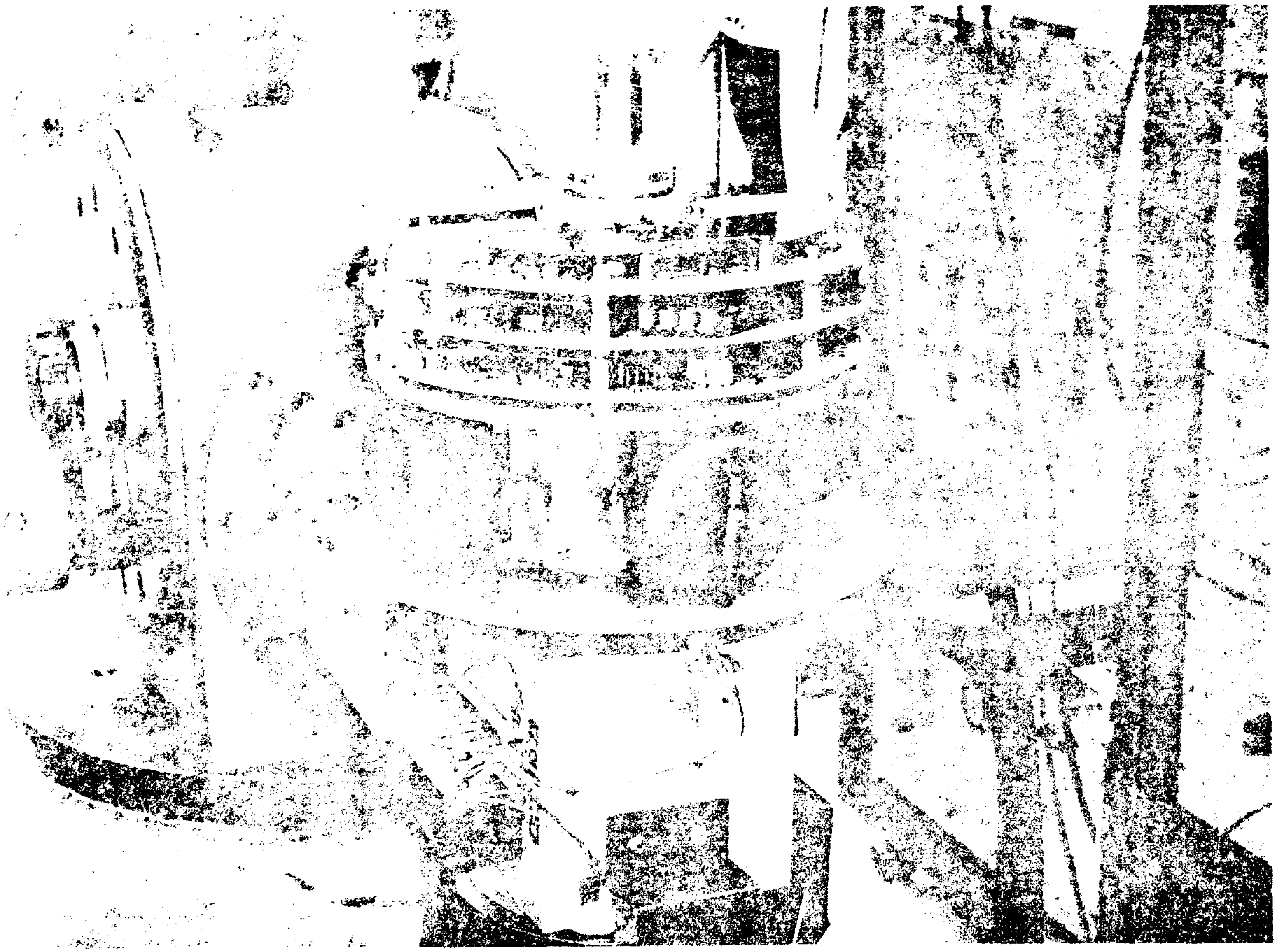
OSDP GGI Rotating Element



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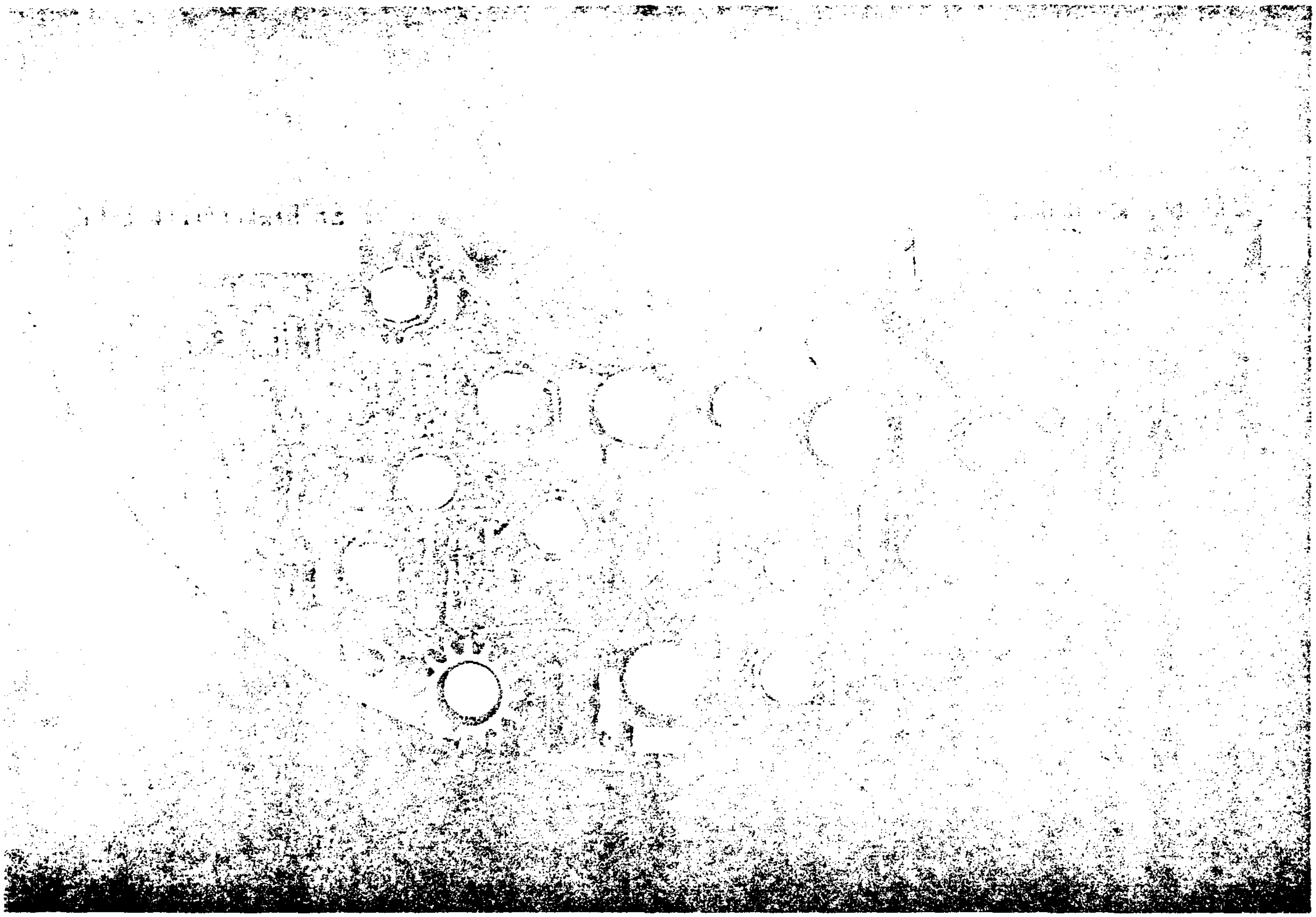
OSDP GGI Constrainment Board



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GGI SLIP RING

- ALL GGIs FABRICATED TO DATE HAVE A SLIP RING CAPSULE OF CONVENTIONAL DESIGN SUPPLIED BY POLYSCIENTIFIC

  REQUIRED MAINTENANCE INTERVAL 3000 HR

- A CONNECTORIZED SLIP RING CAPSULE OF CONVENTIONAL DESIGN TO BE SUPPLIED BY PANDECT PRECISION COMPONENTS LTD (UK) HAS BEEN SELECTED FOR OSDP. GSS FOR GGSS INSTRUMENTS

- THE SLIP RING SELECTION WAS BASED ON AN EVALUATION OF CANDIDATE DESIGNS CONDUCTED DURING 1984

- THE SELECTED DESIGN IS PROJECTED TO HAVE A REQUIRED MAINTENANCE INTERVAL OF NOT LESS THAN 10,000 HR AND POSSIBLY AS HIGH AS 23,000 HR

- MAINTENANCE OF THE NEW DESIGN IS BY PLUG–IN REPLACEMENT AS OPPOSED TO THE CURRENT IN–SITU CLEANING AND RELUBRICATION

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ALTERNATIVE SLIP RING CAPSULE EVALUATION

- POLY–SCIENTIFIC "FLAT BRUSH"
- POLY–SCIENTIFIC "FIBER BRUSH"
- PANDECT STANDARD SINGLE BRUSH
- PANDECT LOW PRESSURE SINGLE BRUSH
- PANDECT TWIN BRUSH
- ENCODER RESEARCH ROLLING ELEMENT
- POLY–SCIENTIFIC ADM TYPE BALL BROTHERS LUBRICATED
- PANDECT SINGLE BRUSH BALL BROTHERS LUBRICATED

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SLIP RING EVALUATION TESTING SCENARIO

- CONTACT RESISTANCE MEASURED IN CIRCUIT PAIRS USING CONSTANT 600 ma CURRENT AND MEASURING VOLTAGE USING A STRIP CHART RECORDER WITH A 50 Hz FREQUENCY RESPONSE

- INSULATION RESISTANCE CIRCUIT TO ADJACENT CIRCUIT MEASURED AT 500V WITH A MEGOHMETER

- ACCELERATED LIFE TESTING WAS ATTEMPTED AT OUTSET BY TESTING ONE SAMPLE AT 3X SPEED AND A SECOND SAMPLE AT 1X SPEED, BUT ABANDONED WHEN TEST DATA INDICATED THAT 3X SPEED CREATED INVALID CONDITIONS

- MEASUREMENTS WERE CONDUCTED ONCE PER WEEK. THE UNIT WAS CONTINUOUSLY RUNNING BUT UNPOWERED BETWEEN TESTS

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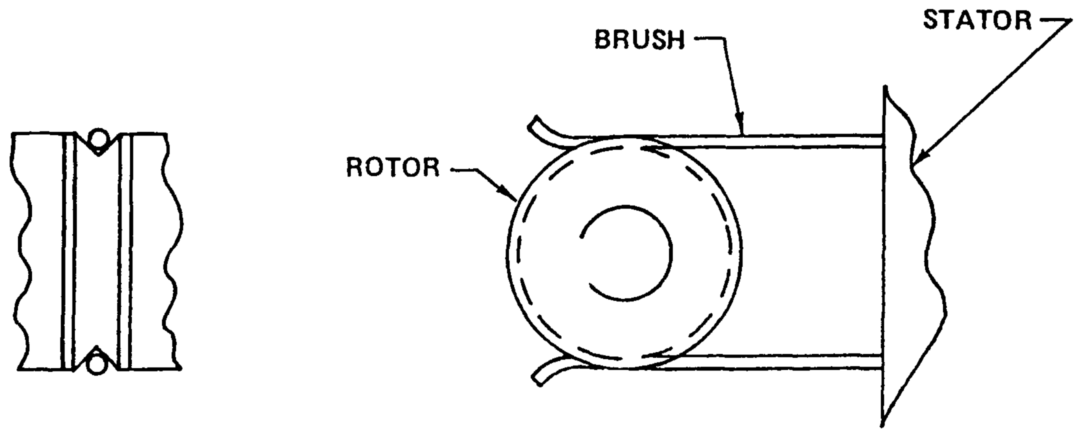
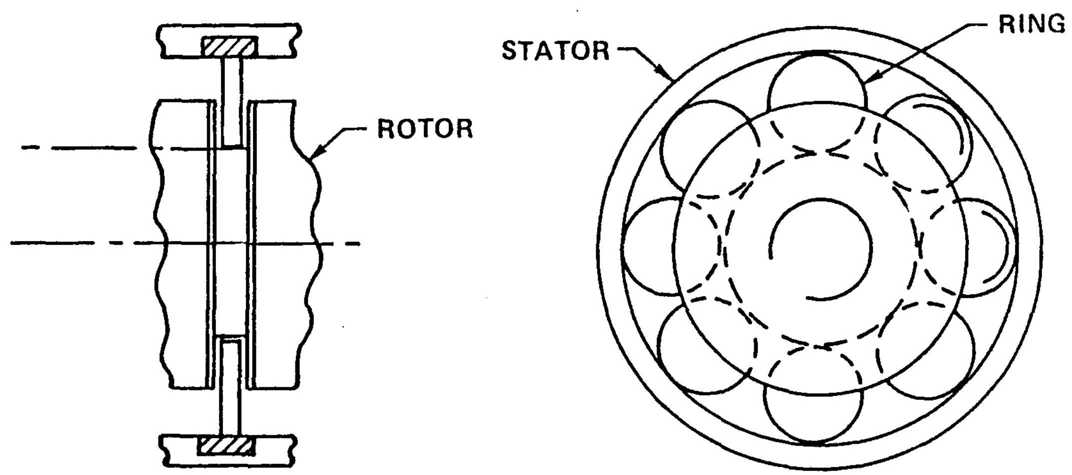
SLIP RING CONFIGURATIONS

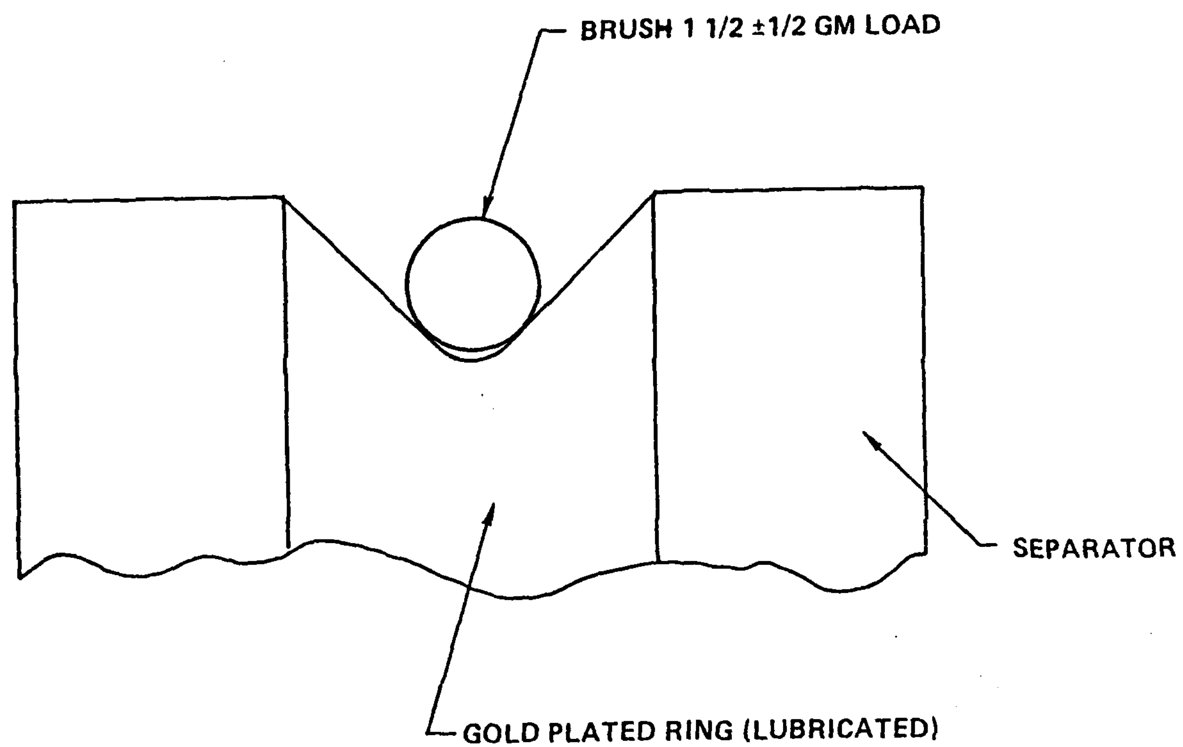


SLIDING CONTACT SLIP RING

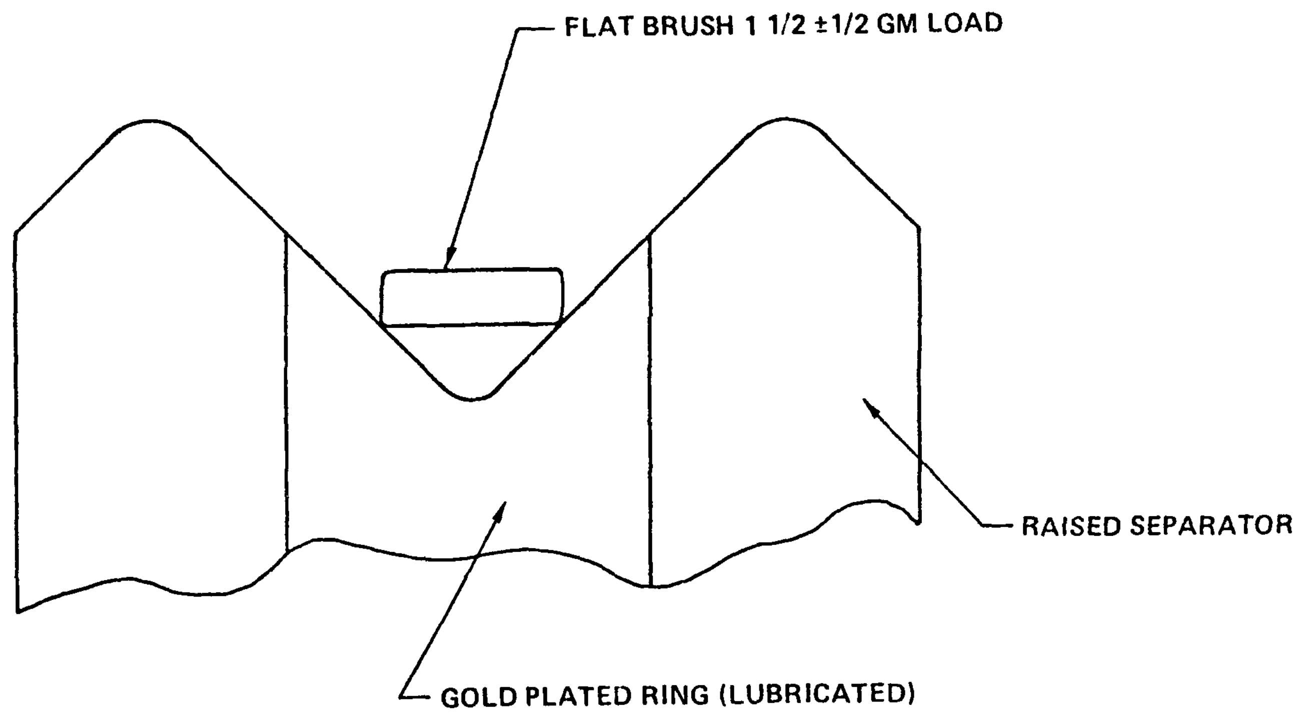


ROLLING ELEMENT SLIP RING

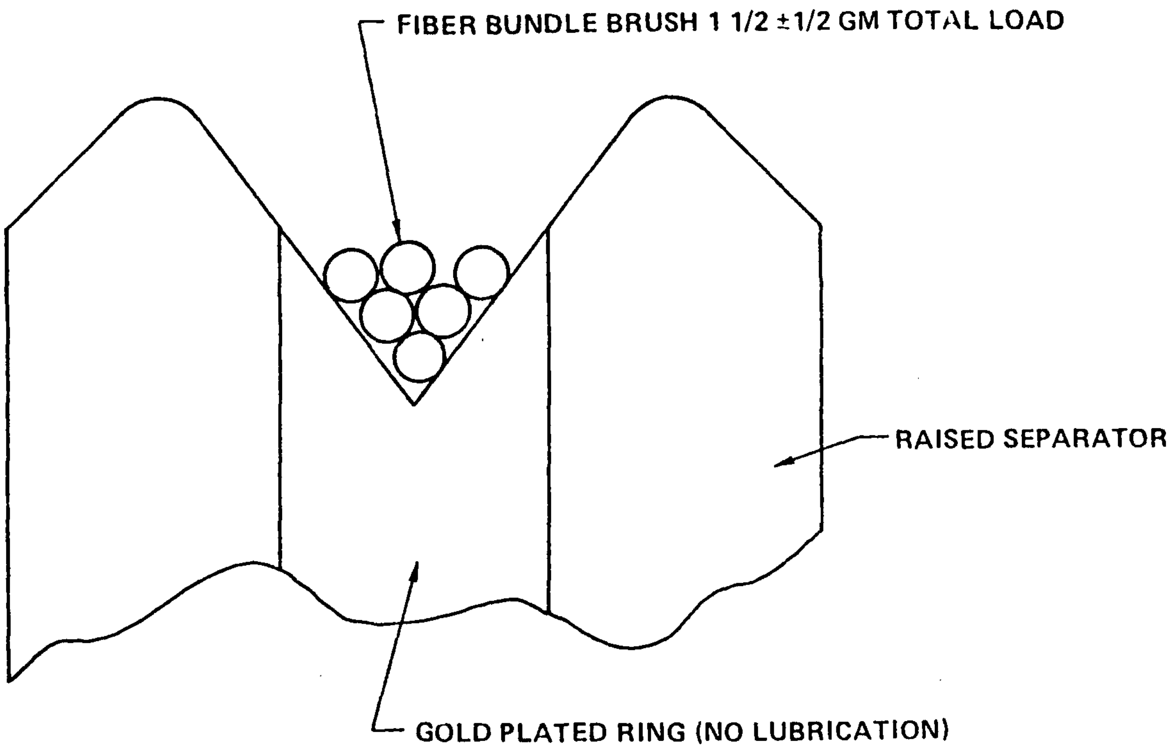
POLY-SCIENTIFIC ADM DESIGN



POLY-SCIENTIFIC FLAT BRUSH DESIGN



POLY-SCIENTIFIC FIBER BRUSH DESIGN



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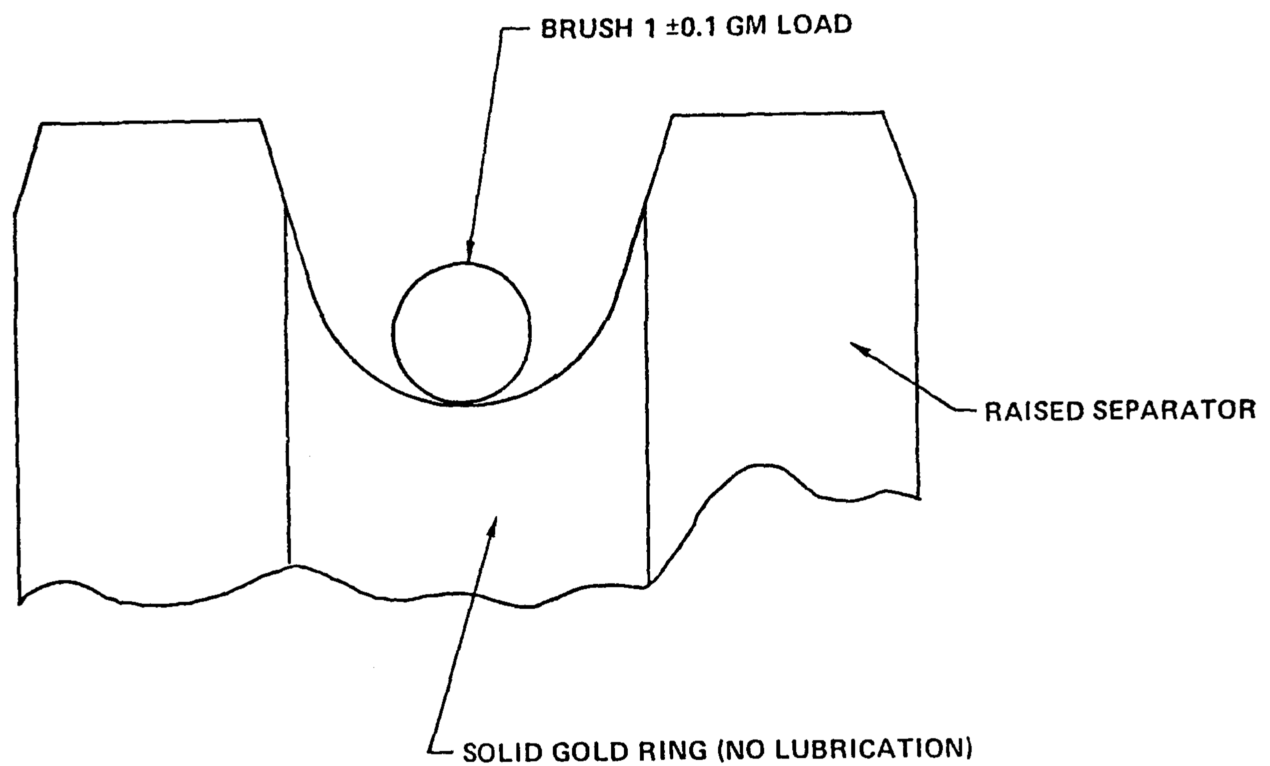
PANDECT STANDARD DESIGN



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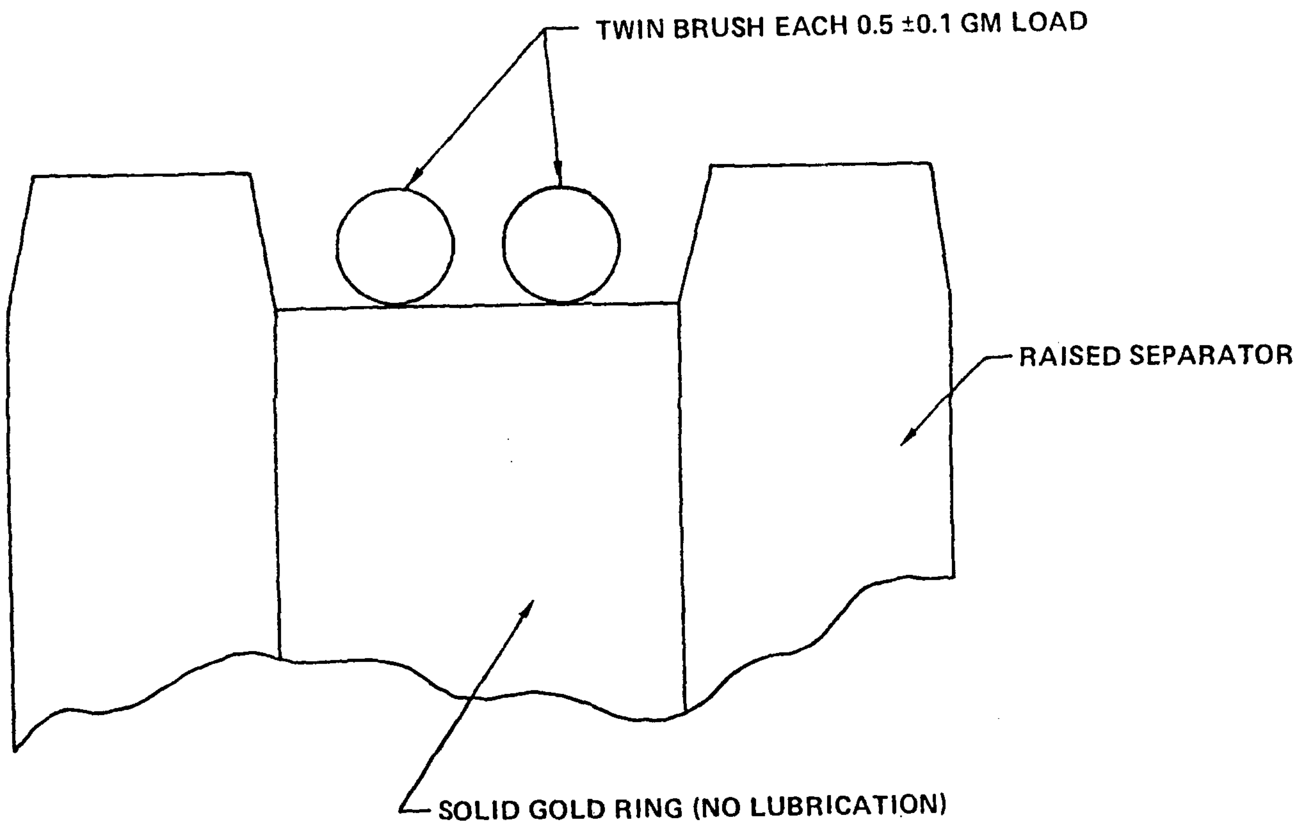
PANDECT TWIN BRUSH DESIGN



SLIP RING CAPSULE EVALUATION TEST RESULTS SUMMARY

SLIP RING CAPSULE	SERIAL NO.	SPEED R.P.M.	HOURS TO FIRST FAILURE	TOTAL TEST HOURS	NO. OF FAILED CCTS AT TEST TERMINATION	
					CONTACT	INSUL.
POLY–SCIENTIFIC FLAT BRUSH	S/N 20	15	600	1,900	4	–
	S/N 21	45	5,500	6,500	2	5
POLY–SCIENTIFIC FIBER BRUSH	S/N 1	15	< 48	120	7	–
	S/N 2	15	1,000	1,500	7	–
	S/N 3	15	500	1,400	5	–
	S/N 4	45		4,000		
ENCODER RESEARCH ROLLING ELEMENT	S/N 1	15	700	5,200	2	–
	S/N 3	15	1,500	3,000	9	–
	S/N 4	45	2,000	2,000	1	–
PANDECT STANDARD	S/N 0990–83	15	*	11,100	–	–
	S/N 0988–83	45	*	10,600	–	–
PANDECT SINGLE LOW PRESSURE BRUSH	S/N 0544–84	15	BEARING PROBLEM	4,480	–	–
PANDECT TWIN BRUSH	S/N 0542–84	15	*	5,600	–	–
PANDECT STANDARD BALL BROS. LUBRICATED	S/N 0989–83	15	*	1,130	–	–
POLY–SCIENTIFIC ROUND BRUSH	S/N 32	15	600	1,580	2	1
BALL BROS. LUBRICATED	S/N 33	15	*	1,400	–	–
PANDECT SINGLE LOW PRESSURE BRUSH BALL BROS. LUBRICATED	S/N 0546	15	670	1,250	4	–

* TEST STILL IN PROGRESS

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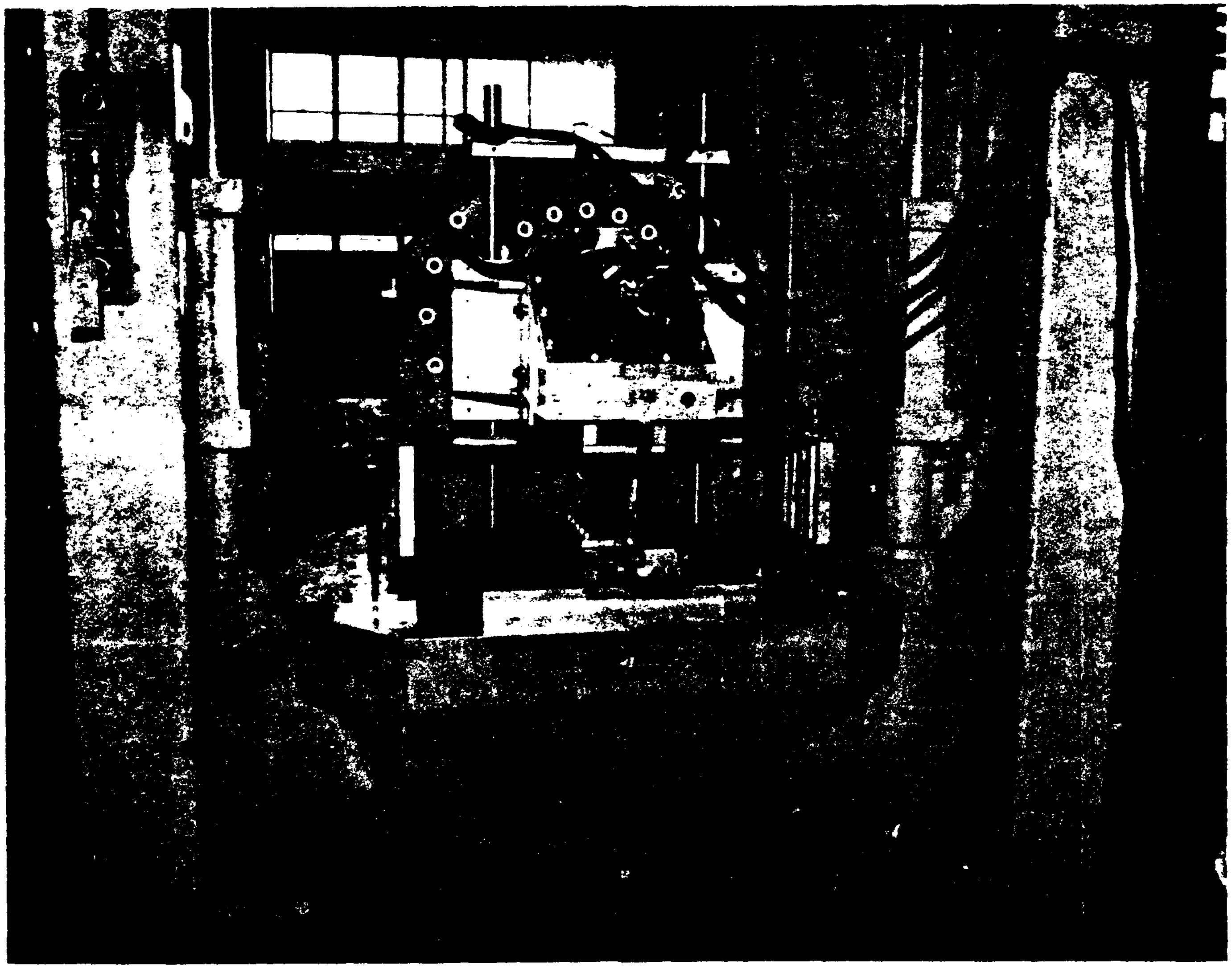
GGI On Shock Test Fixture



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GGI Acceleration Sensitive Error Coefficient Calibration

GGI ACCELERATION SENSITIVE ERROR COEFFICIENTS

SENSITIVITY DIRECTION	INPUT ACCELERATION FREQUENCY	ERROR PROPORTIONALITY
ALONG SPIN AXIS	1Ω	$\Sigma K_4 K_8$
	2Ω	$\Sigma \alpha_o$
	2Ω	(dc ACCEL.). ΣK_7
	3Ω	$\Sigma K_4 K_8$
NORMAL TO SPIN AXIS	1Ω	ΔK_1
	2Ω	(dc ACCEL.). ΣDIFF $K_2 K_5$
	3Ω	

K_1 = SCALE FACTOR

$K_2 = A_i^2$

$K_4 = A_i A_p$

$K_5 = A_o^2$

$K_6 = A_i A_o$

$K_7 = A_p^2$

$K_8 = A_o A_p$

NOTE: IN–LINE BIAS $\alpha\ \Sigma K_6$

CROSS BIAS $\alpha\ \Sigma\ (K_2 \cdot K_5)$

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ORIGINAL GGI COMPENSATION TECHNIQUE TO ACCOUNT FOR AXIAL SHAKE LOOP OFFSET REQUIREMENT

FACTORY GROOMING TECHNIQUE [HORIZONTAL LINEAR MOTION INDUCER]

(1) OPERATE GGI WITH HORIZONTAL SPIN AXIS

(2) APPLY 1Ω ACCELERATION ALONG SPIN AXIS AND SET ΣK_4K_8

(3) APPLY 2Ω ACCELERATION ALONG SPIN AXIS AND FIND AXIAL SHAKE LOOP INTEGRATOR VALUE FOR CORRECT COMPENSATION

(4) OPERATE GGI AT UMBRELLA ANGLE

(5) ACTIVATE AXIAL SHAKE SYSTEM AND FIND OFFSET REQUIRED TO FORCE INTEGRATOR TO OUTPUT FOUND IN STEP (3)

(6) APPLY 2Ω ACCELERATION AND TRIM ΣDIFF K_2K_5

NTV PERTURBATION TECHNIQUE

(1) PITCH PLATFORM TO POSITION GGI WITH HORIZONTAL SPIN AXIS

(2) PERTURBATE GGI ABOUT THE HORIZONTAL α SIN ωpt

(3) DETECT SIN ωpt SIN Ωt AND SIN ωpt COS Ωt AND CHECK ΣK_4K_8

(4) DETECT SIN ωpt AND FIND AXIAL SHAKE LOOP INTEGRATOR VALUE TO NULL SIGNAL

(5) PITCH PLATFORM TO UMBRELLA ANGLE

(6) ACTIVATE AXIAL SHAKE SYSTEM AND FIND OFFSET REQUIRED TO FORCE INTEGRATOR TO OUTPUT FOUND IN STEP (4)

(7) PERTURBATE PLATFORM ABOUT THE UMBRELLA ANGLE AT α SIN ωpt

(8) DETECT SIN ωpt AND CHECK THAT ΣDIFF K_2K_5 SETTING CORRECTLY NULLS SIGNAL. ADJUST IF NECESSARY

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SENSITIVITY TO HIGH SEA STATES

- GGIs GI AND ADM S/N 104 EXHIBITED A SIGNIFICANT NOISE INCREASE IN HIGH SEA STATES
- INVESTIGATIVE TESTS CAPITALIZING ON THE AVAILABILITY OF A VERTICAL MOTION INDUCER ESTABLISHED
- $\Sigma\alpha_0$ LOOP OFFSET AND Σ DIFF K_2/K_5 COMPENSATIONS WERE MIS–SET
- THE MIS–SETTING WAS CAUSED BY THE TECHNIQUE USED WHICH ASSUMED A NEGLIGIBLY SMALL K_7 ERROR COEFFICIENT. (K_7 WAS FOUND TO BE NEGLIGIBLY SMALL IN GGIs USED FOR DEVELOPMENT OF THE AXIAL SHAKE SYSTEM.)
- IN OSDP BREAKBOARD UNIT G1, K_7 WAS FOUND TO BE 4.1 $\mu g/g^2$ AND IN ADM S/N 104 WAS 5.6 $\mu g/g^2$, IN BOTH CASES BEING AT LEAST AN ORDER OF MAGNITUDE TOO LARGE TO BE NEGLECTED.

NOTE: THE AXIAL SHAKE LOOP AUTOMATICALLY DETECTS AND CORRECTS FOR A K_7 ERROR COEFFICIENT SO THAT THE EXISTENCE OF A K_7 IN ITSELF IS NOT A PROBLEM.

CONCLUSIONS AND SOLUTION

- CALIBRATION OF ALL ERROR COEFFICIENTS CANNOT BE ACCOMPLISHED BY PLATFORM PERTURBATION ALONE
- BASED ON MEASUREMENT DATA ONLY THE ΣDIFF K_2K_5 COEFFICIENT HAS THE POTENTIAL OF CHANGING SIGNIFICANTLY WITH TIME
- BY ADDING VERTICAL LINEAR INPUTS COMPLETE EFFECTIVE COMPENSATION OF ALL COEFFICIENTS AND LOOP OFFSET CAN BE ACCOMPLISHED BY FACTORY GROOMING
- THE ΣDIFF K_2K_5 COEFFICIENT CAN BE CALIBRATED BY PLATFORM PERTURBATION WITH THE GGI IN ITS NORMAL UMBRELLA ANGLE ATTITUDE

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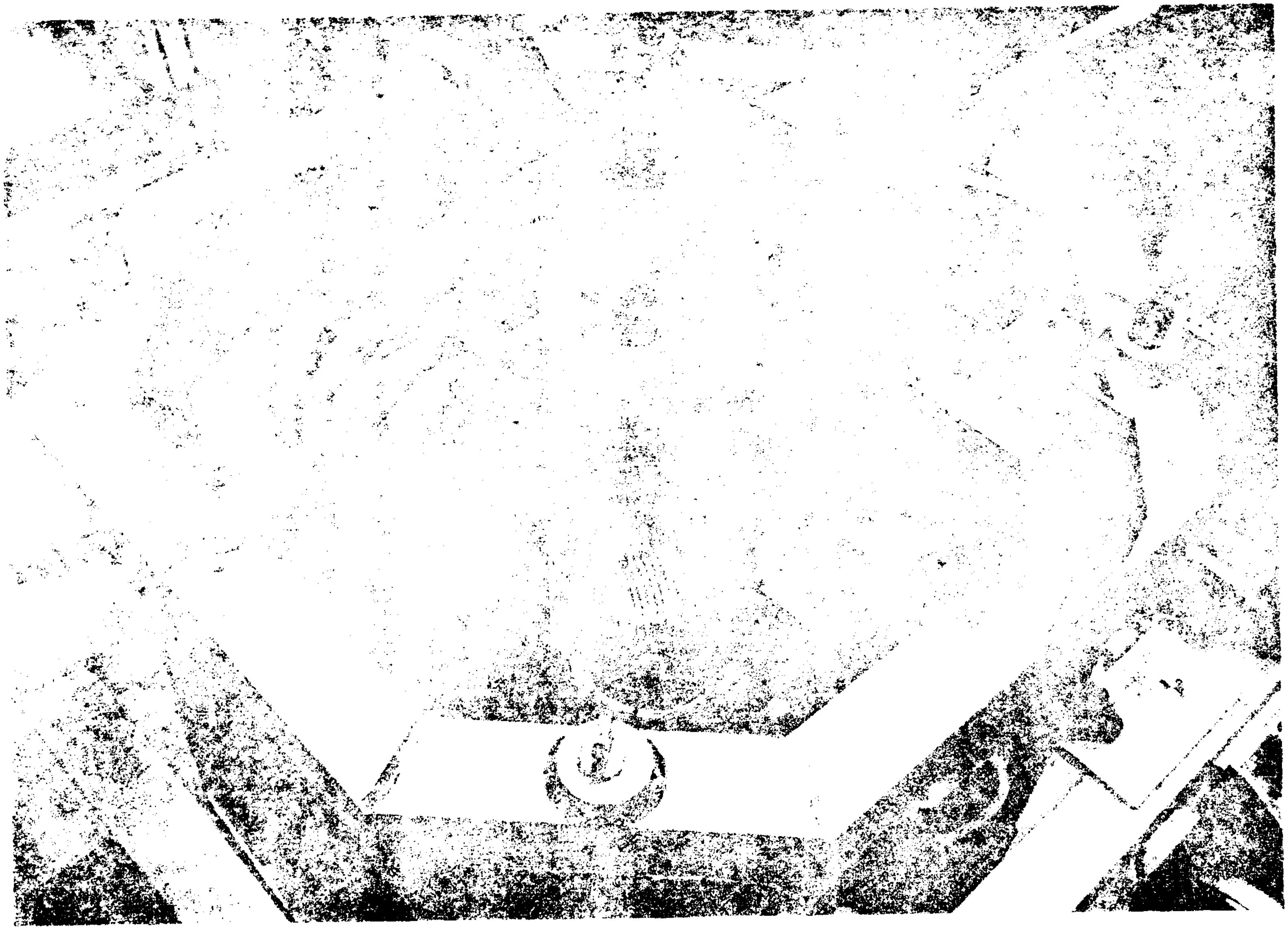
GGI Mounted In Dual Axis Motion Inducer



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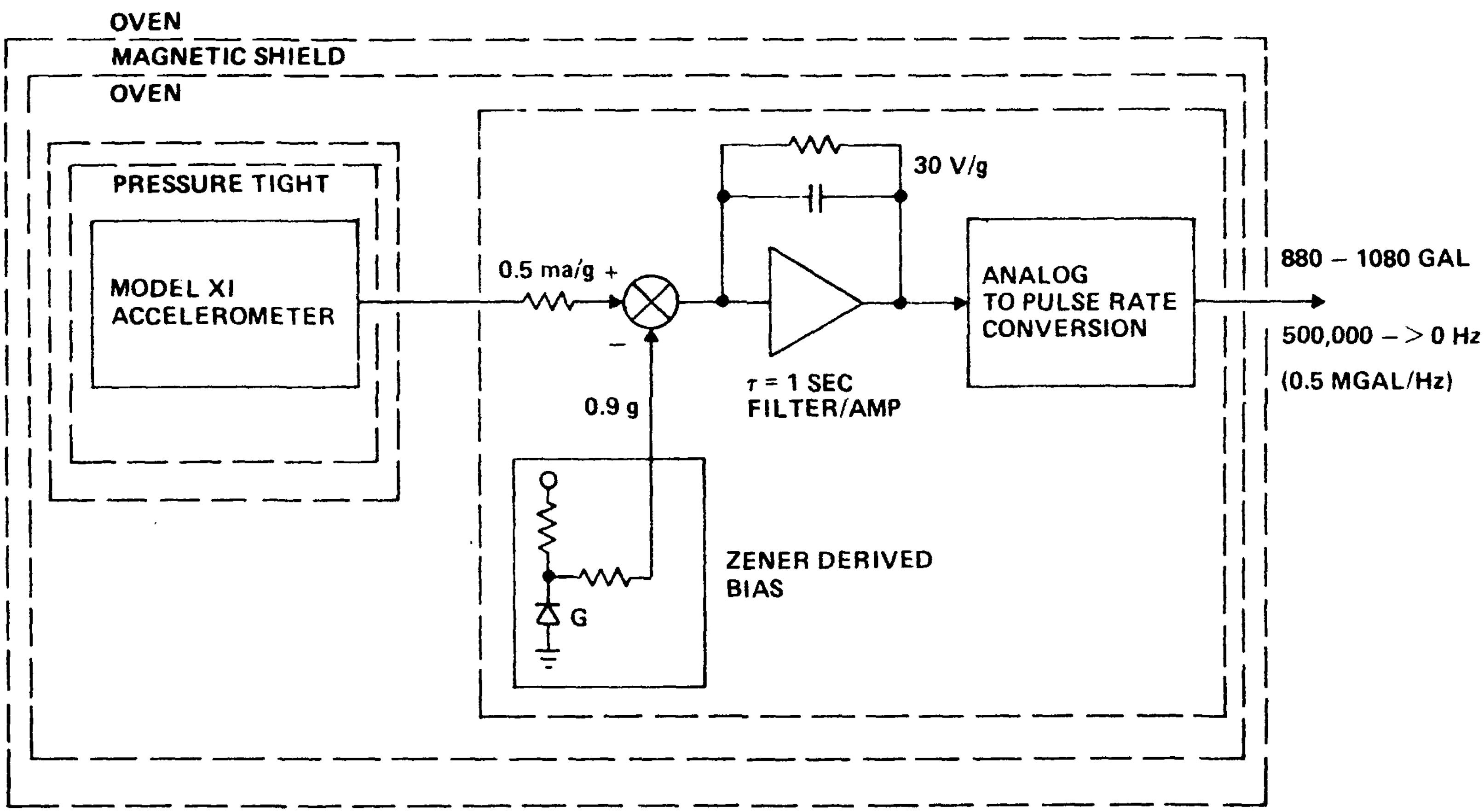
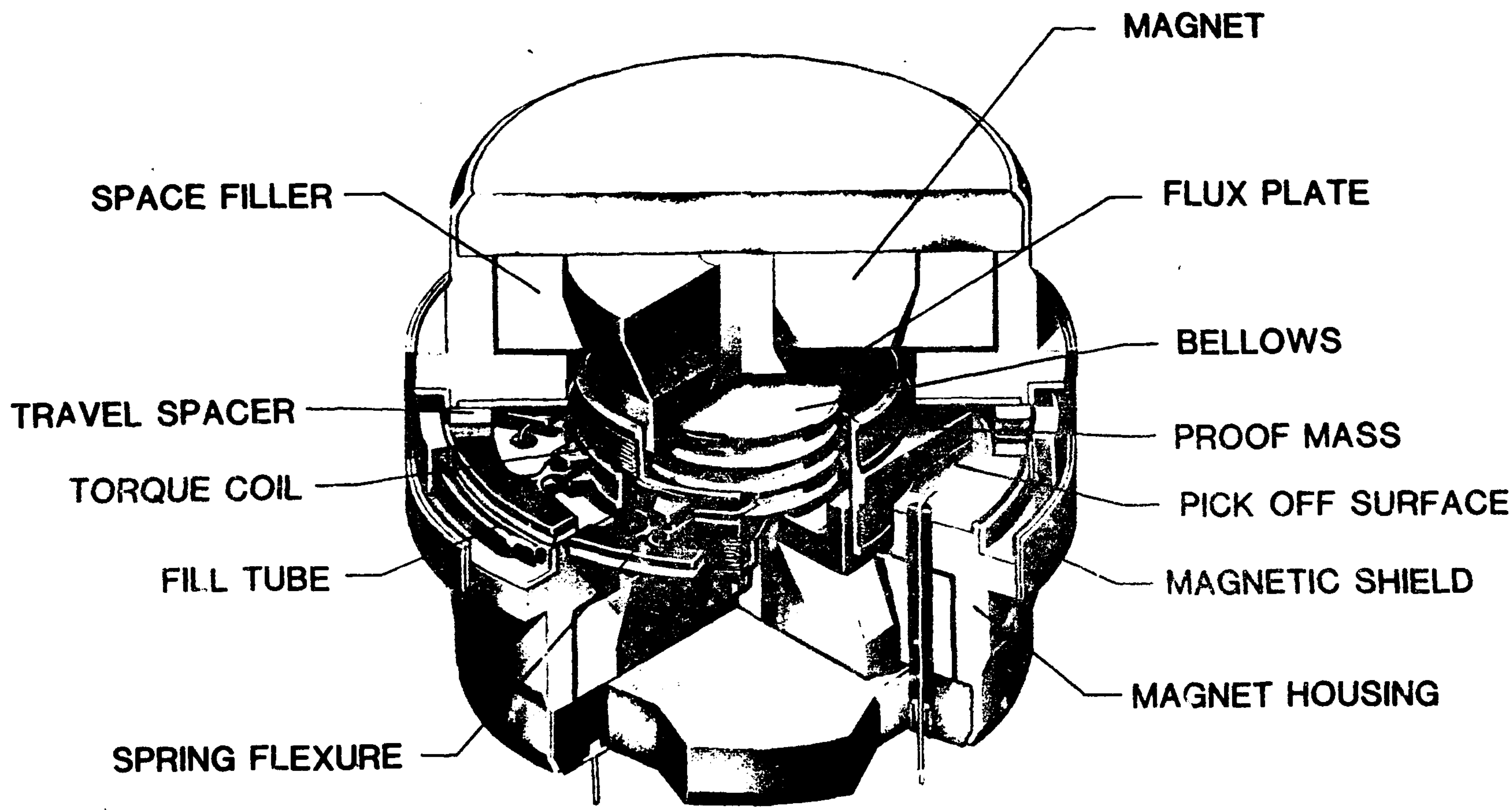
Gravimeter Module Assembly (GMA)

GMA BLOCK DIAGRAM



MODEL XI ACCELEROMETER



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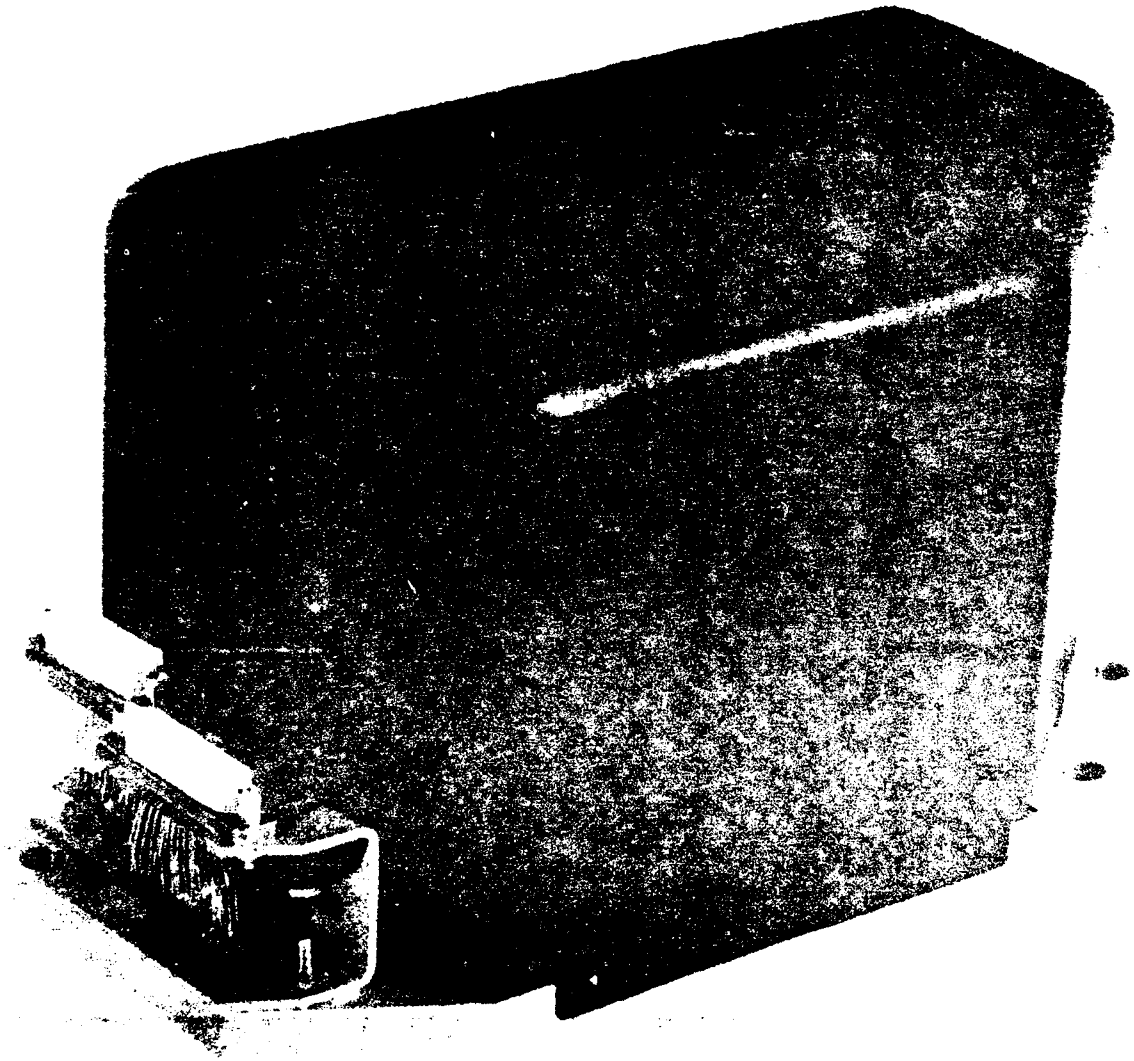
Gravimeter Module Assembly (Engineering Model)

Gravimeter Module Assembly (Engineering Model)



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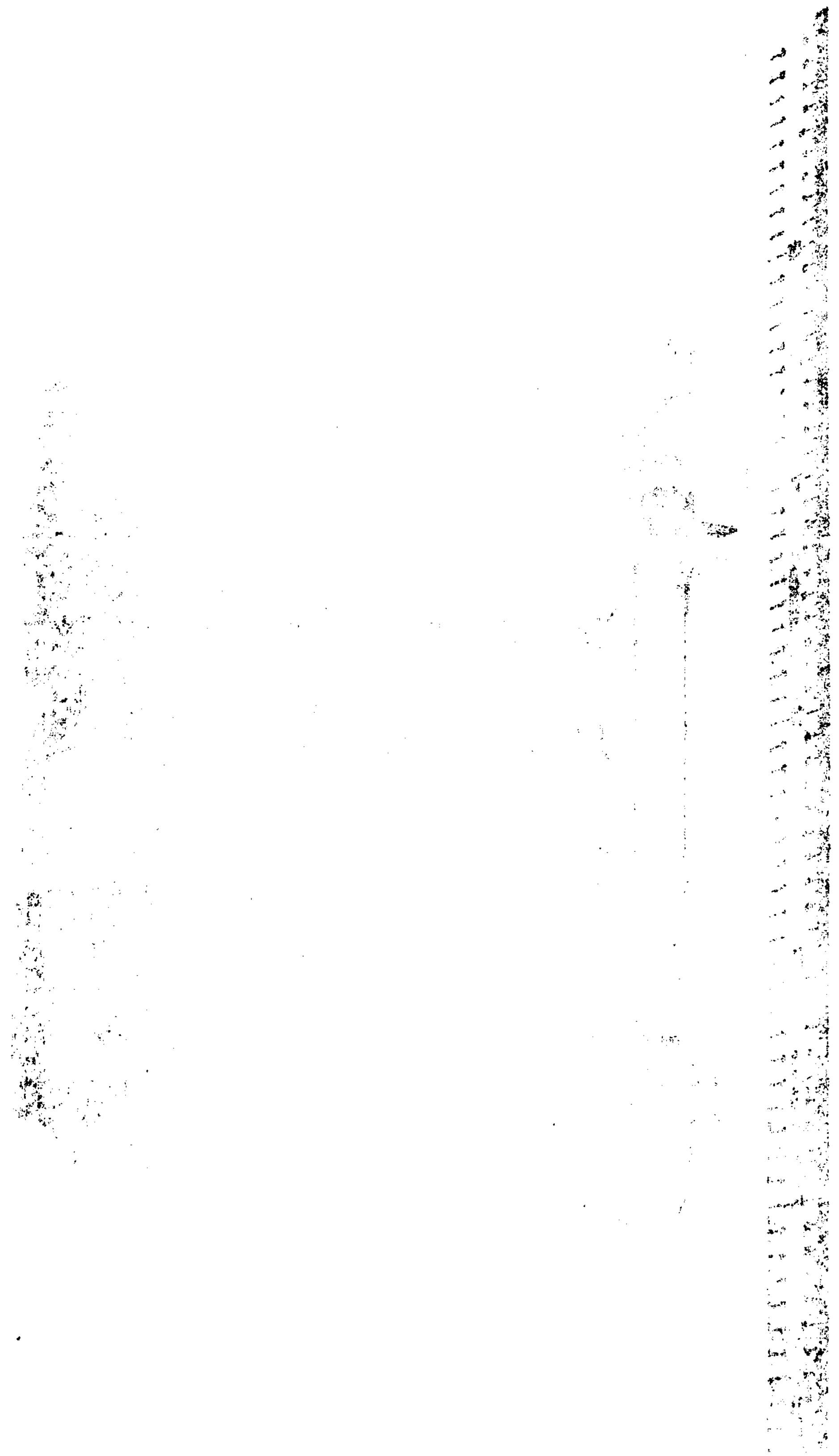

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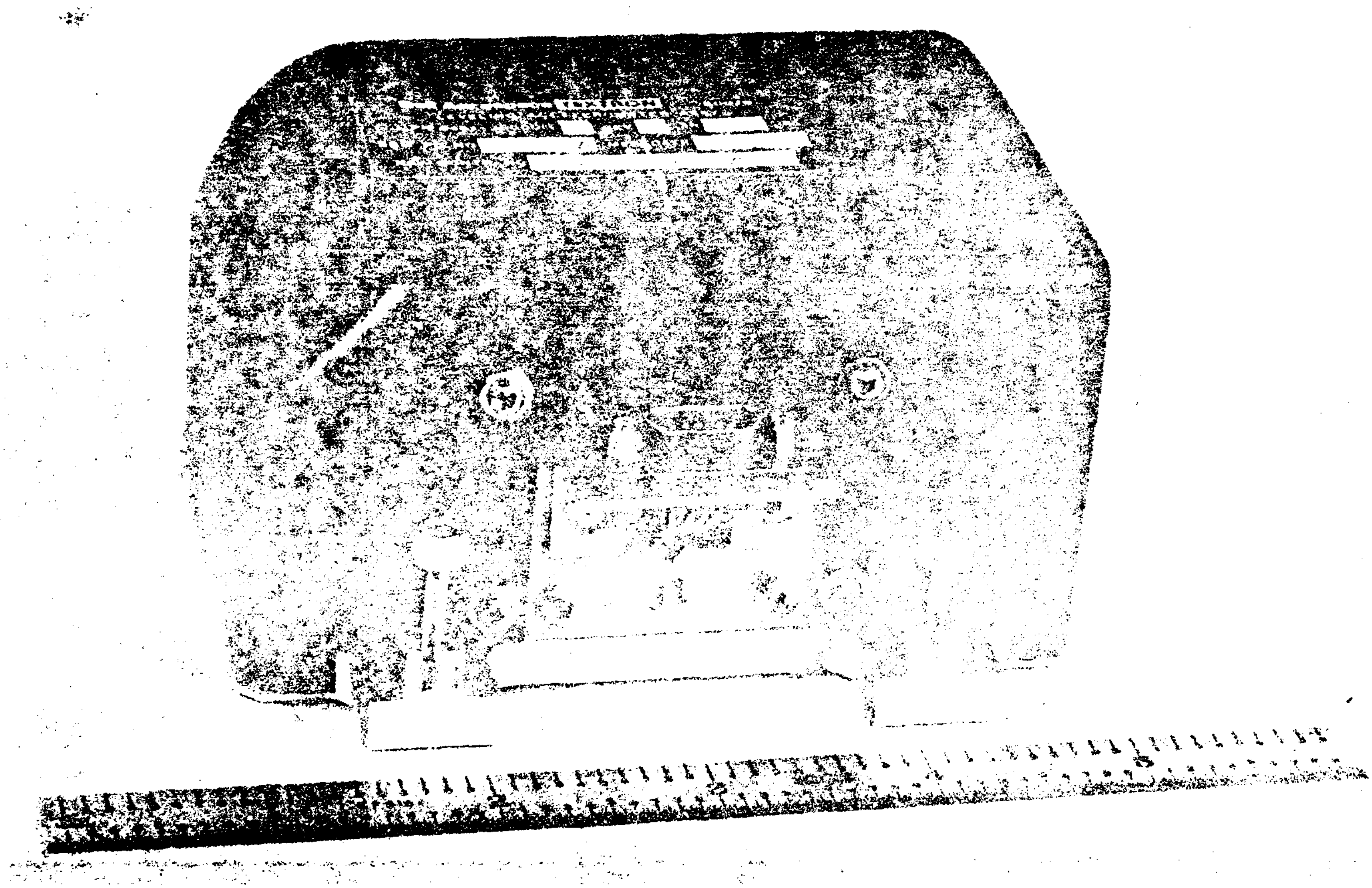
Leveling Accelerometer Assembly



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GMA TEST EQUIPMENT AND UTILIZATION

- SCREEN MAJOR COMPONENTS/ASSEMBLIES PRIOR TO ASSEMBLY

TEST STATION	PARAMETER	DURATION DAYS	NO. OF RACKS
• ACCELEROMETER AND CONSTRAINMENT	NOISE/DRIFT	90	3
• ZENER DIODE	NOISE/DRIFT	90	4
• OPERATIONAL AMP	NOISE/DRIFT	30	1
• DIGITIZER	NOISE/DRIFT	30	1
• TEMPERATURE CONTROL REGULATION	FUNCTION	1	1
• GMA SETUP			
• GROOMING/PREFAT	NOISE DRIFT RESOLUTION ENVIRONMENT	90	5
• ALIGNMENT		1	1
• GMA FAT			
• DATA ACQUISITION	NOISE DRIFT	45	3
• DATA REDUCTION	RESOLUTION	–	2
• DEVELOPMENT	(SAME AS FAT DATA ACQUISITION)		2

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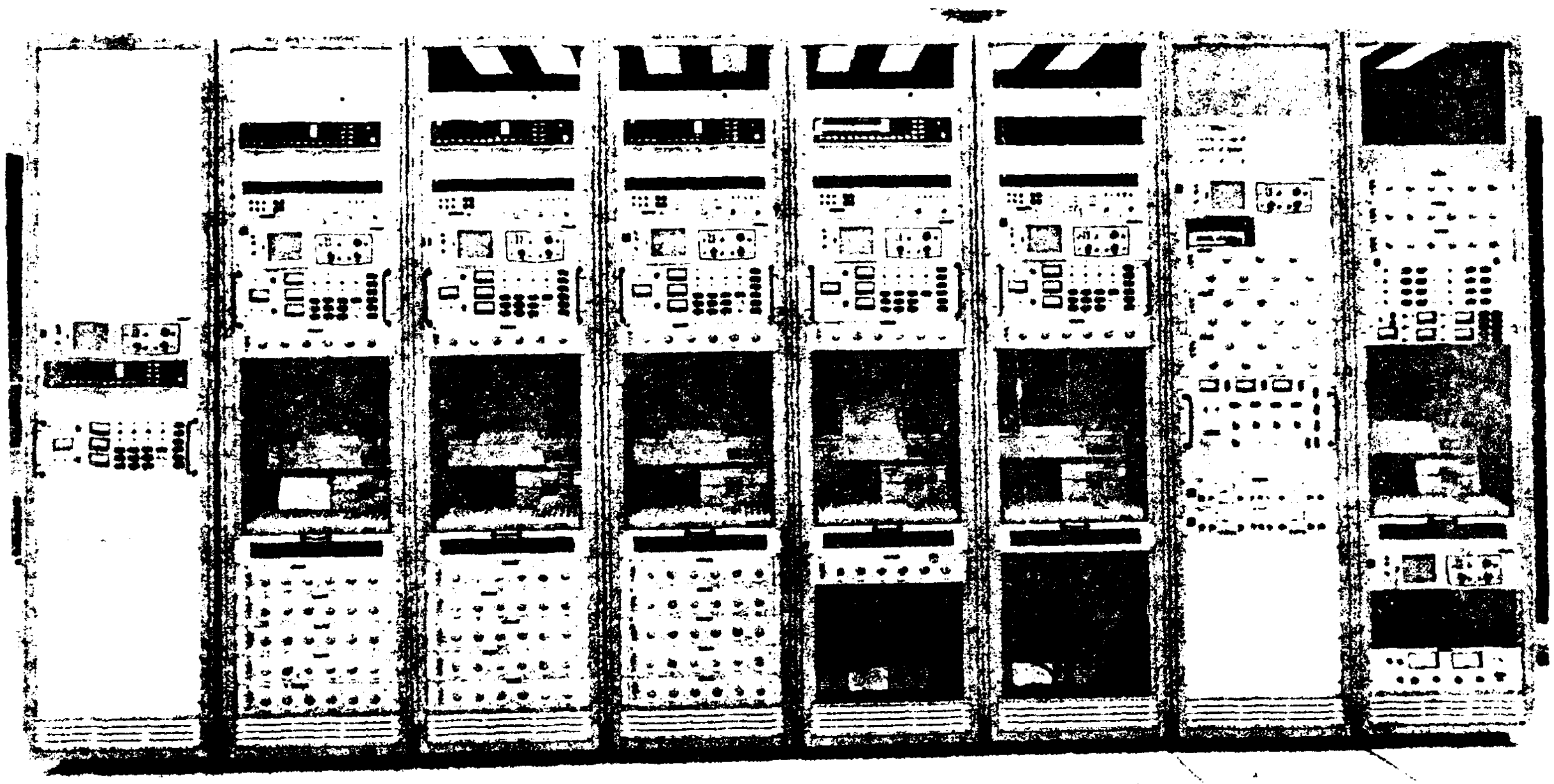
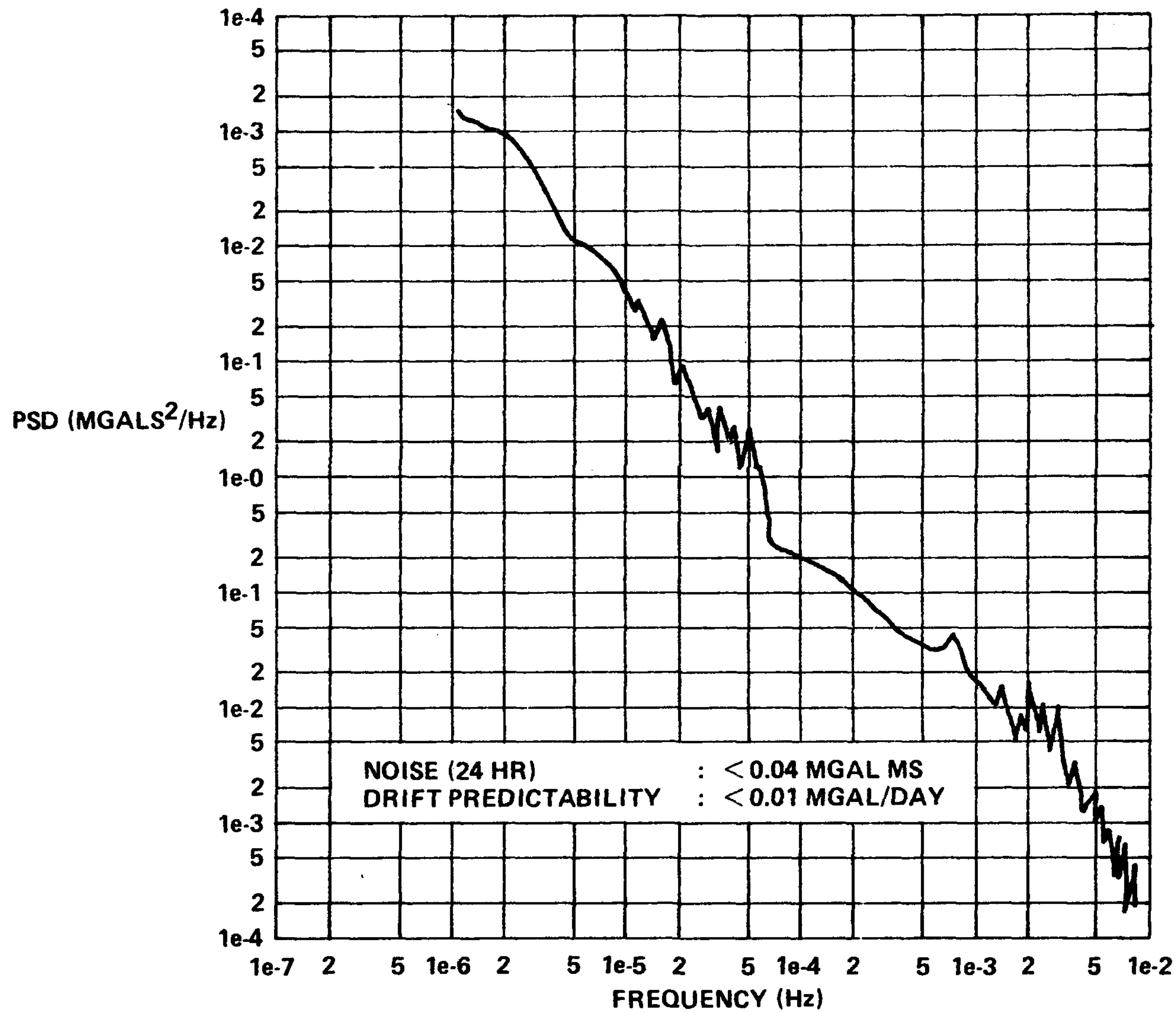
GMA Grooming Stations



IR&D BGM (HEAVY PROOF MASS MODEL XI) POWER SPECTRAL DENSITY L/S CORRECTED GRAVITY

PENDULOSTY : 507 DYNE CM/g
SCALE FACTOR : 5.2 MA/g



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GRAVITY SURVEY SHIPS USING BGM 3

NAVAL OCEANOGRAPHIC OFFICE

- USNS WYMAN
- USNS AESS
- USNS DUTTON
- USNS BOWDITCH

MOBIL OIL COMPANY

- MV SEARCH

SEISMOGRAPH SERVICES LTD

- MV SEIS SEARCH

COLUMBIA UNIVERSITY (LAMONT LABORATORY)

- MV CONRAD

WESTERN GEOPHYSICAL

- MV NELSON

US GEOLOGICAL SURVEY

US NAVY (SPERRY)

- USNS VANGUARD

Electronic Circuit Board Development

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STEPS IN THE DESIGN OF ELECTRONIC CIRCUITRY BOARDS

1. MEANINGFUL ELECTRONIC DEVELOPMENT ORGANISATION
   - ALONG PROJECT (TASK) LINES
   - APPOINT COMPETENT TASK LEADER
   - RESPONSIBILITY FROM CONCEPTUAL DESIGN TO DETAIL DESIGN AND ANALYSIS, BREADBOARD TEST, PARTS PROCUREMENT, FABRICATION TO TEST OF FINAL ARTICLES
2. SOUND PARTITIONING
   - COMPLETE FUNCTION(S) ON ONE BOARD
   - HARDWARE FIRMWARE TRADE-OFFS
   - MAINTAINABILITY/TESTABILITY CONSIDERATIONS
3. CAREFUL DESIGN AND ANALYSIS
   - MINI DESIGN REVIEWS WITH INDIVIDUALS IN PEER GROUP
   - PROPER USE OF GURUS
   - LIVING SCHEMATIC
4. LARGE SCALE BREADBOARDS
   - SAME FUNCTIONS AS ON FINAL PRINTED CIRCUIT BOARD
   - MODIFY AS REQUIRED (WIRE WRAPPED VECTOR BOARDS)
   - TEST THOROUGHLY
   - KEEP THOROUGH TEST AND DESIGN NOTES
5. PARTIAL INTEGRATION OF LARGE SCALE BREADBOARDS
   - EARLY UNCOVERING OF INTERACTIONS REQUIRING MODS
   - CONTINUE BREADBOARD INTEGRATION TO FULL SUBSYSTEM
   - INTEGRATION OF BREADBOARD SUBSYSTEM WITH MECHANICAL HARDWARE
6. CONDUCT PARALLEL ACTIVITIES
   - START PRINTED CIRCUITRY ART WORK AND PURCHASE ELECTRONIC COMPONENTS FOR A FEW SYSTEMS WHEN REASONABLE CONFIDENCE OF DESIGN HAS BEEN ACHIEVED
   - THE COST OF PARTS NOT USED OR CORRECTIVE PRINTED CIRCUITRY ARTWORK IS USUALLY MUCH LESS THEN A SCHEDULE DELAY

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GEC ELECTRONIC BOARD COMPLEMENT

NAME OF BOARD	FUNCTION	NO.
CPU	PCMP, LCMP	4
CPIO	PCMP, LCMP	4
PROM	PCMP, LCMP	5
RAM	PCMP, LCMP	7
TIMER & A/D	PCMP, LCMP	4
DISCRETE	PCMP, LCMP	4
D/A A/D	PCMP, LCMP	4
REFERENCE CLOCK	PCMP, LCMP	4
NTDS INTERFACE	PCMP	1
NTDS CONTROL	PCMP	1
VELOCITY ACCUMULATOR	PCMP	1
S/D	PCMP	1
GMS INTERFACE	PCMP	2
GMA MONITOR	PCMP	2
AC REFERENCE	PLAT STAB	1
JITTER MEASUREMENT	PLAT STAB	1
DEMODULATOR/FILTER	PLAT STAB	3
GIMBAL CONTROL	PLAT STAB	3
GYRO CONTROL	PLAT STAB	1
POWER AMP ASSEMBLY	PLAT STAB	3
SYNCHRO REF/TEMP CONTROL	PLAT STAB	1
GYRO SYNC REF	PLAT STAB	1
MDAC	LCMP	3
COMP AMP	GGI	3
BATTERY CHARGER	PS	1
GGI TEMP CONTROL	GGI	3
TOTAL 6 IN. X 9 IN. BOARDS		68

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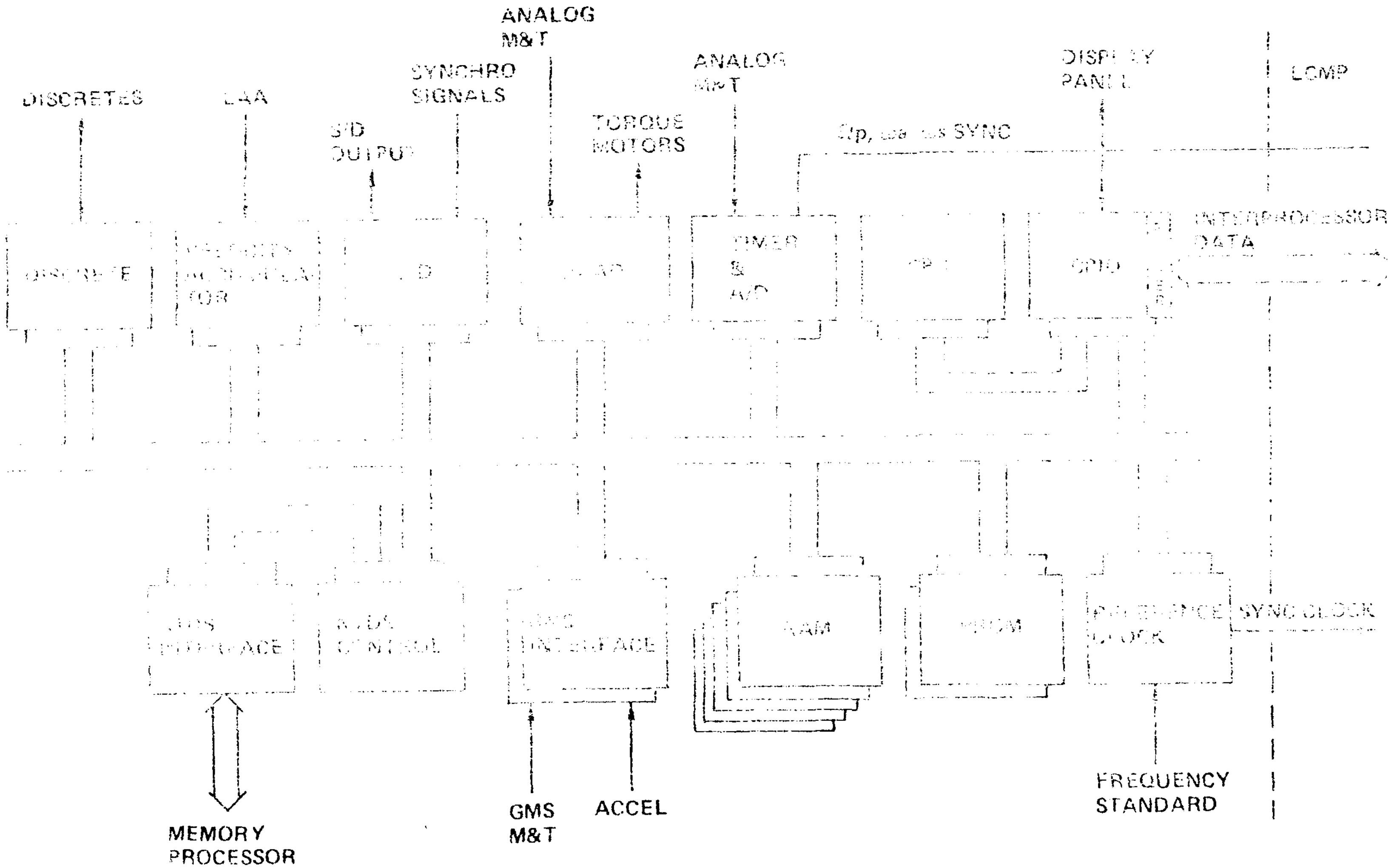
PCMP BLOCK DIAGRAM



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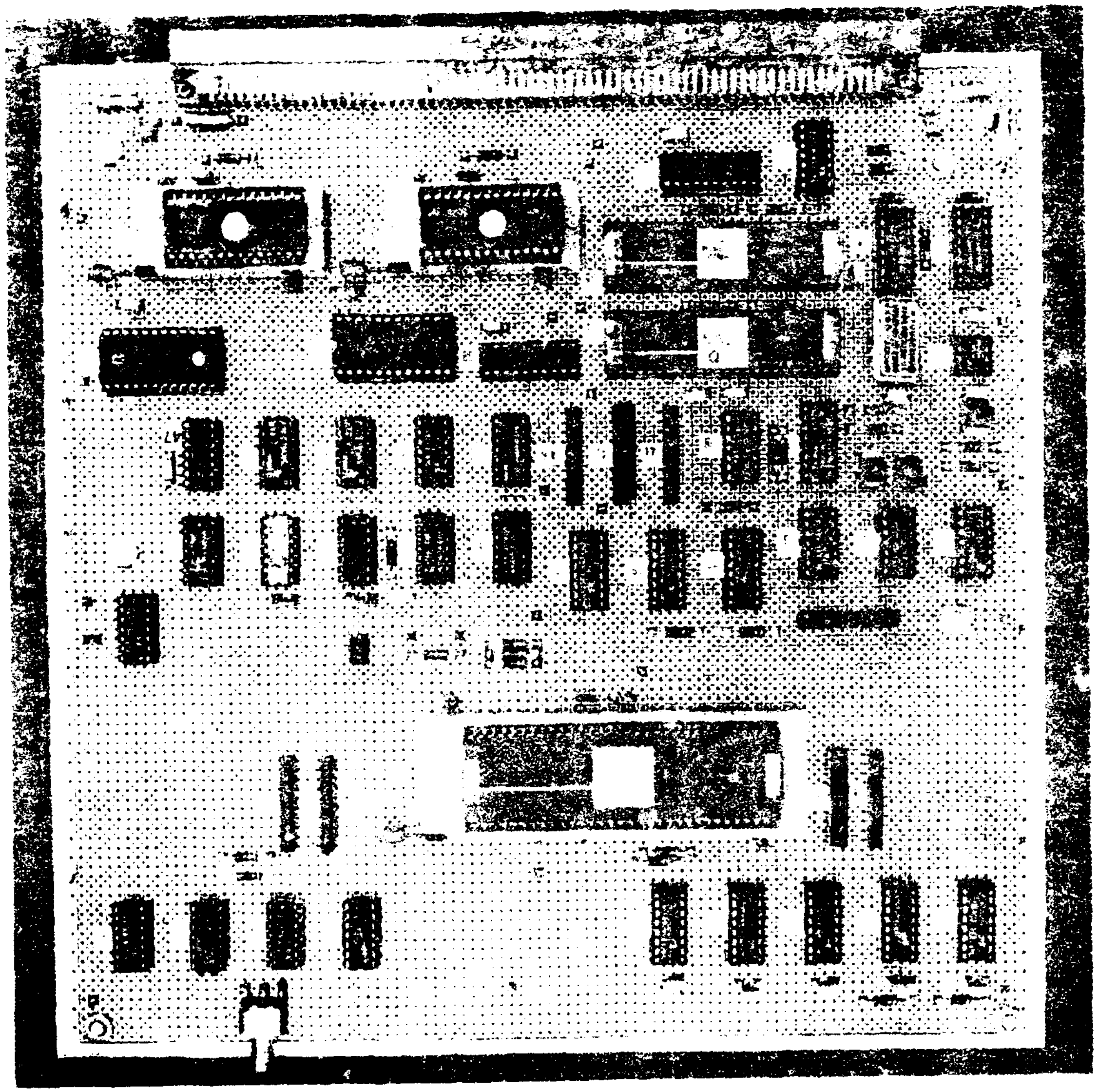
CPU Breadboard



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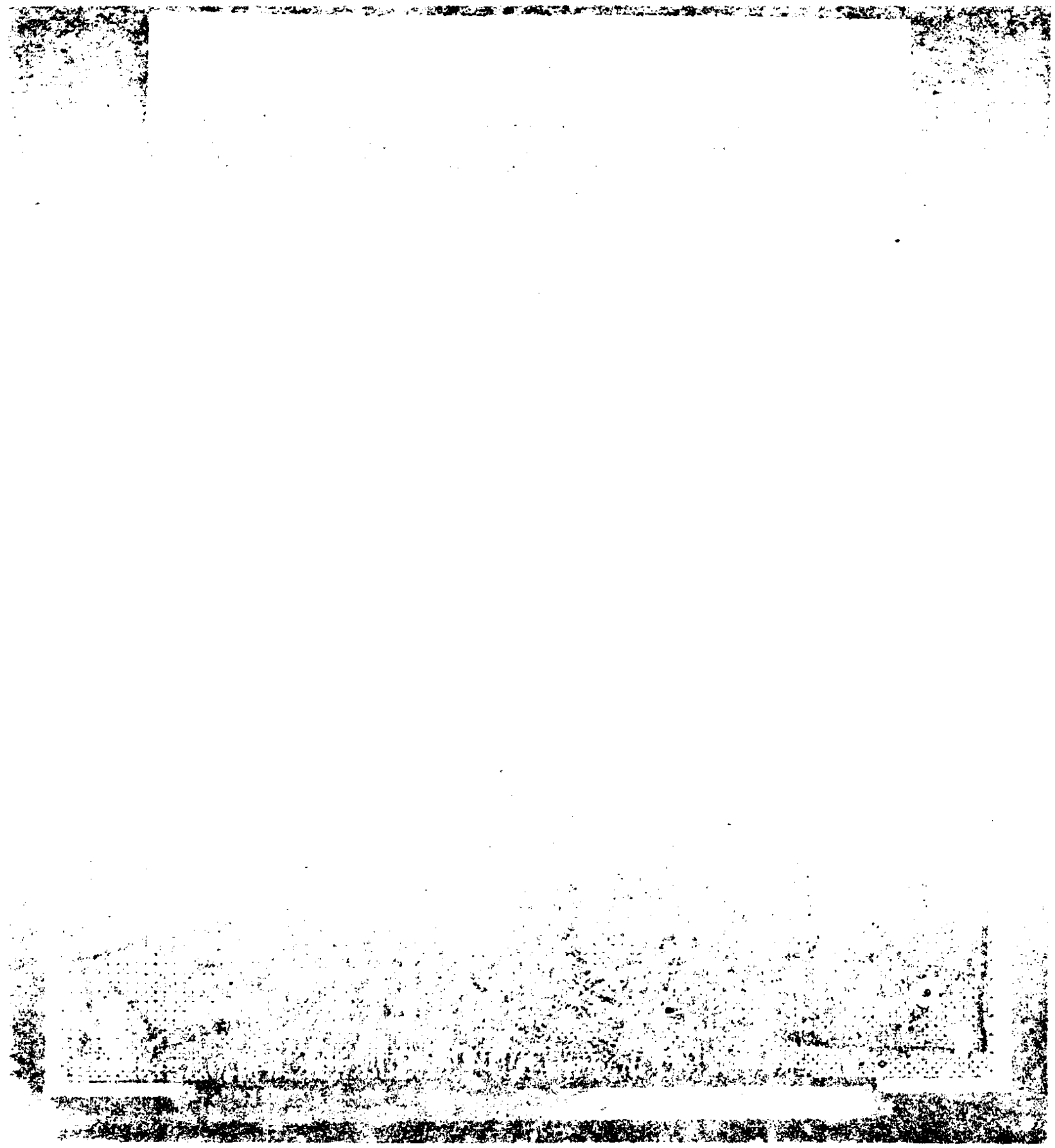
CPU Breadboard



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CENTRAL PROCESSING UNIT – CPU

- 68000 MICROPROCESSOR
- MICROPROCESSOR OSCILLATOR – 16 MHz
- RAM – 4 K BYTES
- ERASEABLE PROM – 16 K BYTES, ON–BOARD PROGRAMMABLE
- INTERRUPT HANDLER
- I/O FUNCTION ADDRESS DECODERS
- MICROPROCESSOR RAM AND EPROM DECODERS
- PROGRAMMABLE REAL TIME CLOCK
- M/T FUNCTIONS

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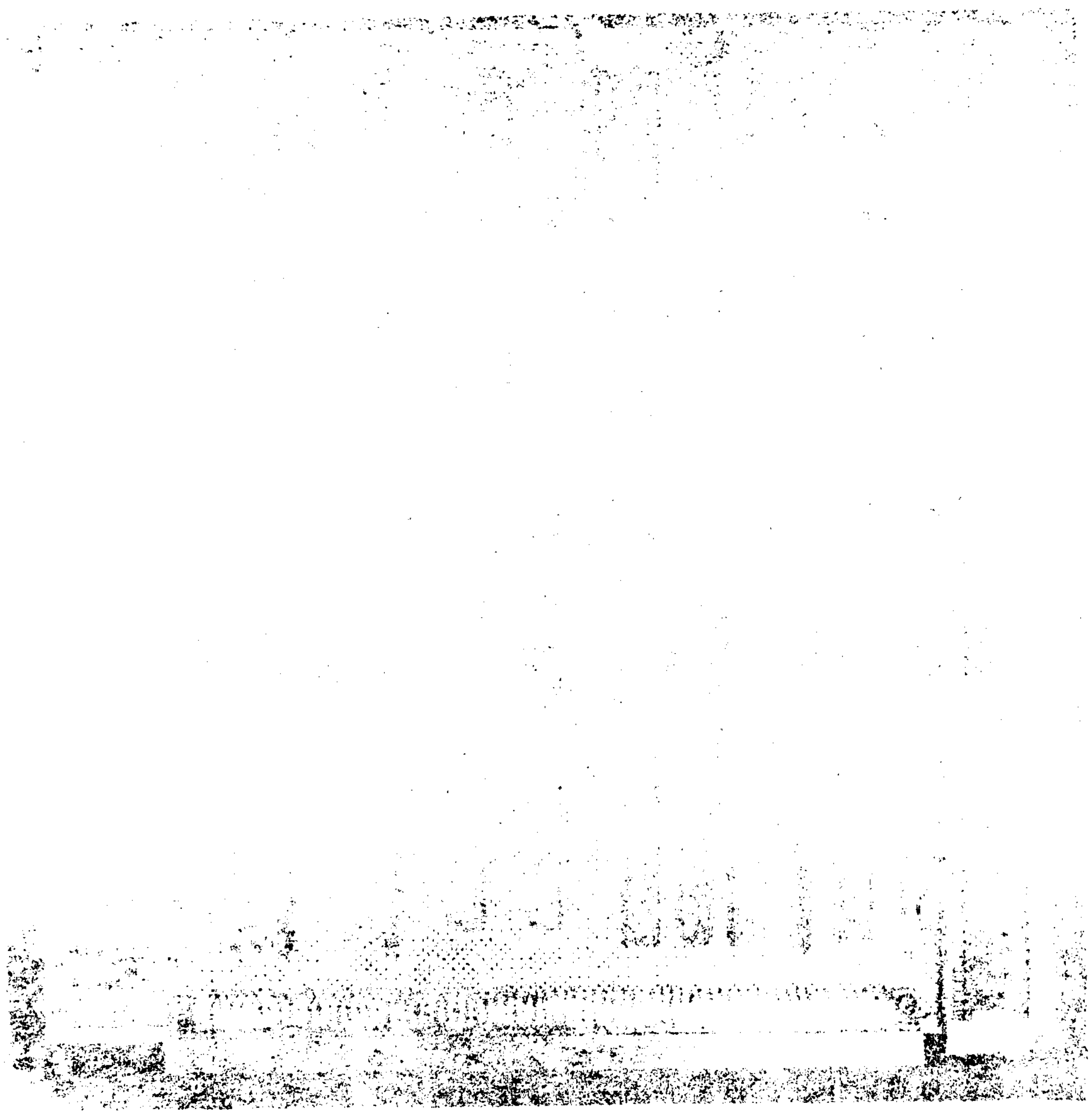
CPI/O Breadboard



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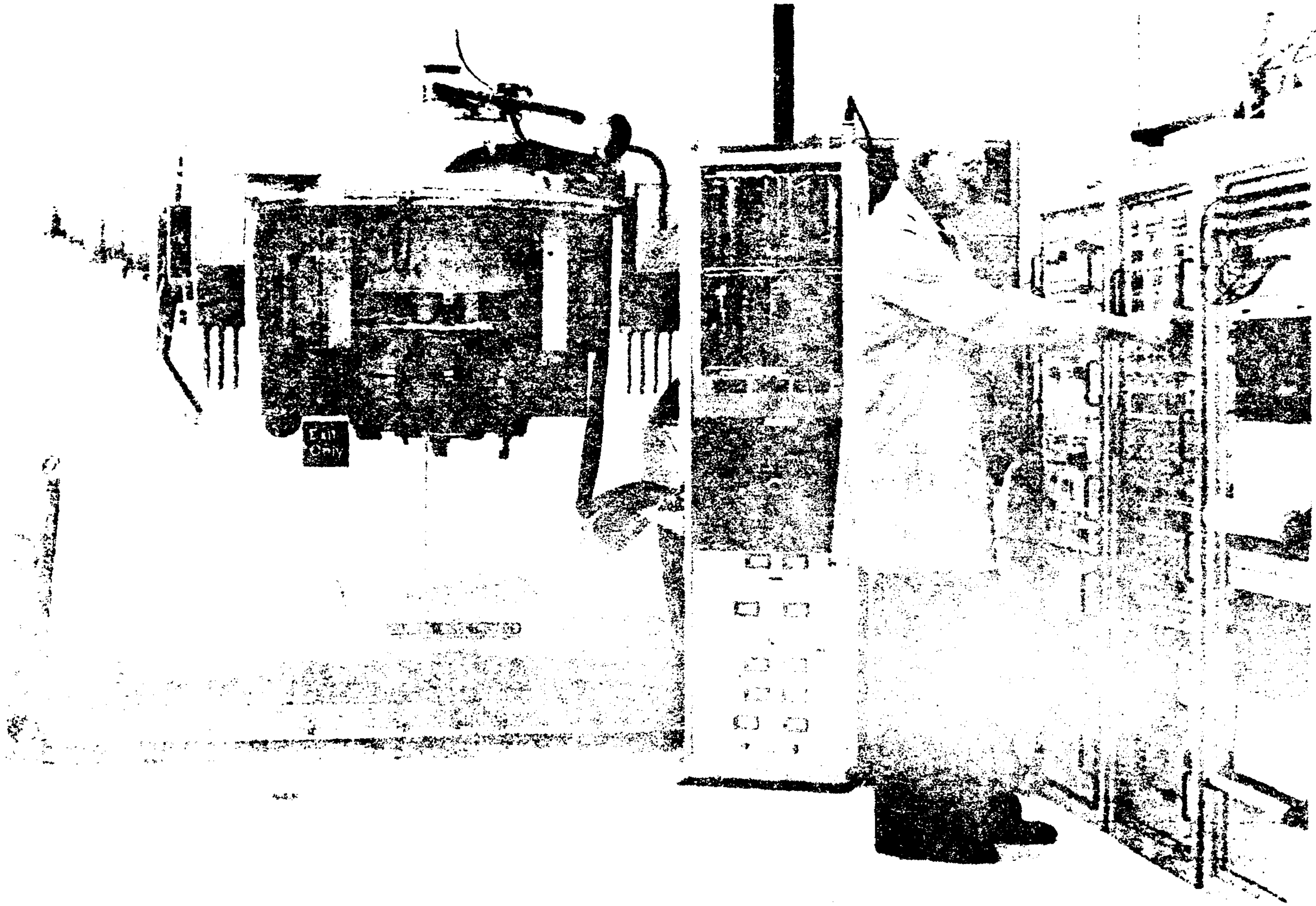
CENTRAL PROCESSING INPUT/OUTPUT – CPIO

- ADDRESS BUS DRIVERS
- DATA BUS DRIVERS
- CONTROL BUS DRIVERS
- FRONT PANEL INTERFACE
- RS–232 SERIAL DATA LINKS – 2
- INTERPROCESSOR DATA LINK
- ERASEABLE PROM – 96 K BYTES, ON–BOARD PROGRAMMABLE
- M/T FUNCTIONS

PCMP Cage I Breadboard Integration Test

Platform Stabilization Cage Breadboard Integration Test With ADM System No. 2



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PCMP CAGE 2

- MODIFY MOTOROLA EDUCATOR CARD
  - BUS INTERFACE
  - INTERRUPT HANDLING
  - ADDRESS DECODING

- TEST NTDS CONTROL CARD
  - BUS COMPATIBILITY
  - NTDS SLOW CONTROL FUNCTIONS
  - CONTROL AND STATUS REGISTERS
  - FIFO's AND FIFO CONTROL
  - LOOP BACK M/T CAPABILITY
  - TIMEOUT CIRCUITRY
  - INTERRUPT HANDLING

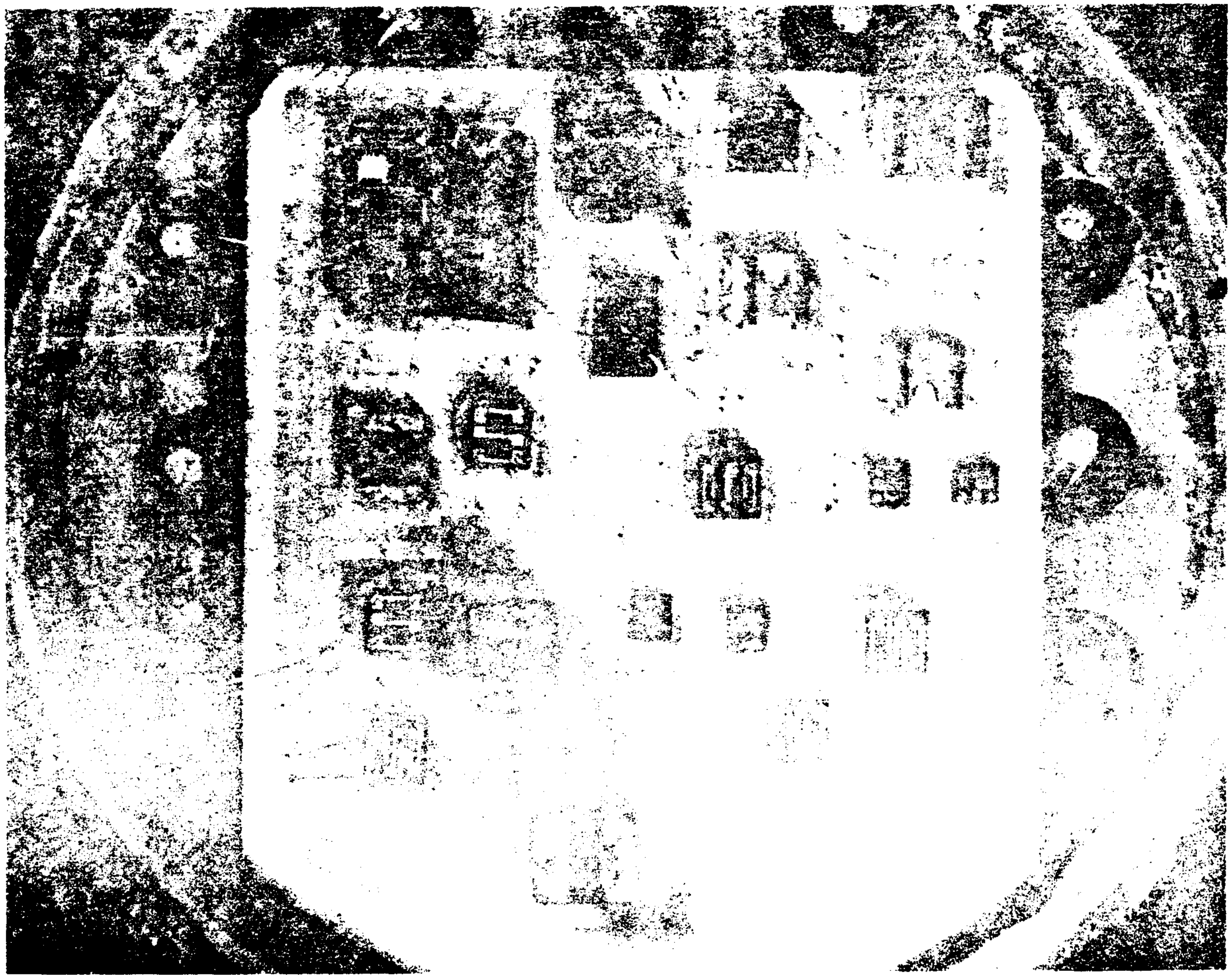
- TEST NTDS INTERFACE CARDS (2 CARD SET)
  - COMPATIBILITY WITH NTDS CONTROL CARD I/O
  - LOOP BACK CAPABILITY WITH NTDS CONTROL CARD

- TEST GMS INTERFACE CARD
  - BUS COMPATIBILITY
  - DISCRETE I/O AND PARITY GENERATION
  - D/A LATCHING MECHANISM
  - A/D CONVERSION AND LATCHING
  - OPTICAL ISOLATOR AND PULSE COUNTER

- TEST GMS MONITOR CARD
  - SIGNAL TRANSFER TO GMS INTERFACE CARD

- TEST CAGE
  - POWER DISTRIBUTION
  - TERMINAL STRIP CONNECTION INTEGRITY
  - INTERACTIVE TEST BETWEEN BOARDS

Hybrid Accelerometer Preamp



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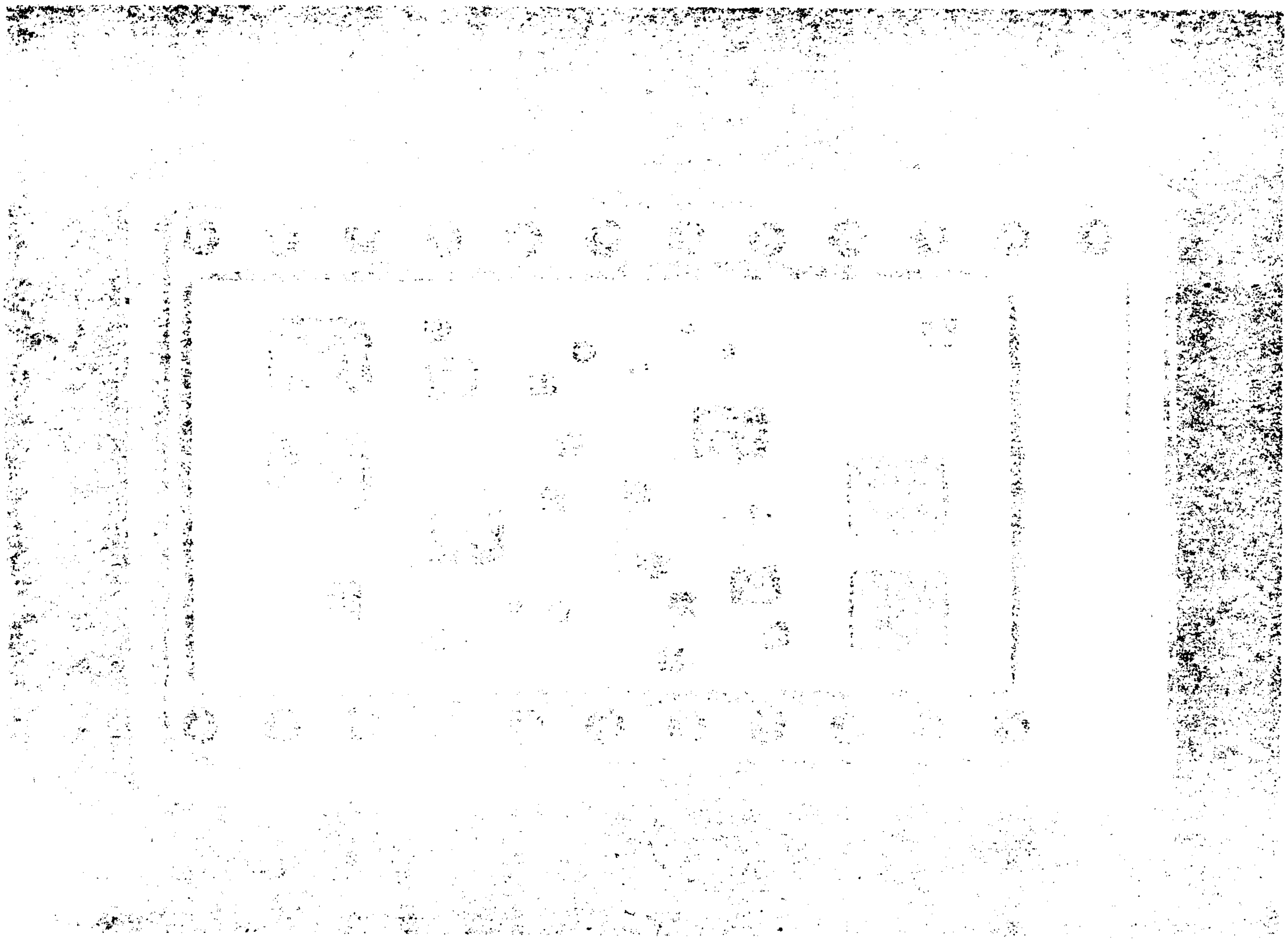
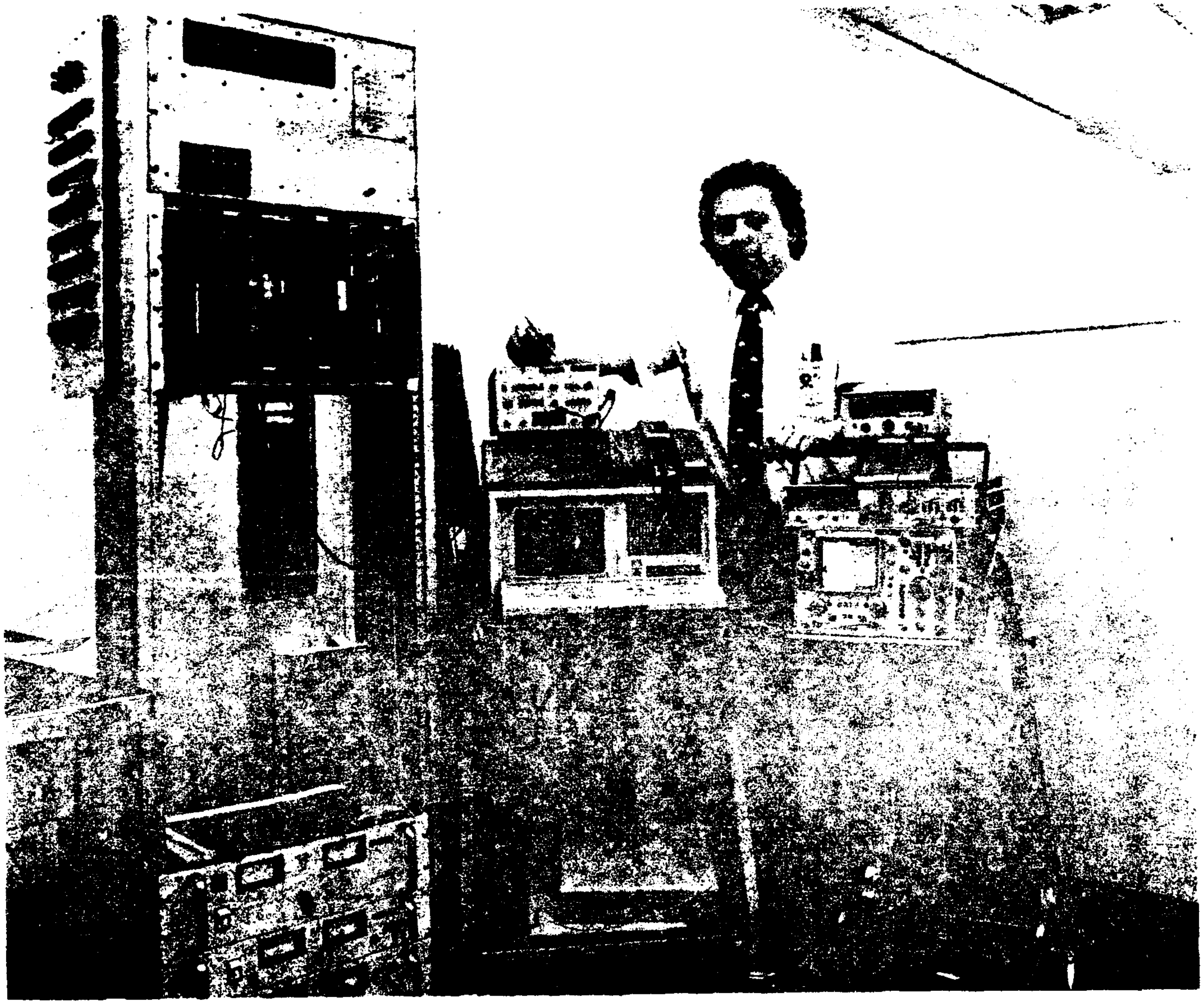
Hybrid Dual Amplifier



PCMP Cage I Breadboard Integration Test



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PCMP CAGE 1

- TEST CPU AND CPIO
  - REAL TIME CLOCK
  - WATCHDOG TIMERS
  - ADDRESS DECODERS
  - INTERRUPT HANDLER
  - FRONT PANEL I/O
  - SERIAL PORT I/O
  - M & T LATCHING
  - EPROM AND RAM
- TEST REFERENCE CLOCK
  - BUS COMPATIBILITY
  - CONTROL AND STATUS REGISTERS
  - INTERRUPT HANDLING
  - CLOCK CALIBRATION
  - M/T CONTROL
- TEST TIMER FOR A/D AND DAAD
  - BUS COMPATIBILITY
  - INTERRUPT HANDLING
  - SINE ωa AND SINE ωs GENERATORS
- TEST DISCRETE
  - BUS COMPATIBILITY
  - DISCRETE I/O AND PARITY GENERATION
- TEST VELOCITY ACCUMULATOR AND S/D CONVERTER
  - BUS COMPATIBILITY
  - PULSE FREQUENCY MULTIPLEXERS
  - M/T CONTROL
- TEST CAGE
  - POWER DISTRIBUTION
  - TERMINAL STRIP CONNECTION INTEGRITY
  - INTERACTIVE TEST BETWEEN BOARDS

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Hybrid Bonding Work Station

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BONDING WORKSTATIONS

THESE TWO MACHINES ARE USED TO MAKE THE INTERCONNECTIONS BETWEEN THE CHIP ELEMENTS AND THE SUBSTRATE AND ALSO THE CASE BINS AND THE SUBSTRATE. THE TECHNIQUE USED IN THERMOSONIC BONDING OF 1 MIL GOLD WIRE

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Marathon Automatic Electronic Board Test Machine

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Marathon Automatic Electronic Board Tester
Program Development Station

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GSS Dedicated Facility

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MOVING BASE GRAVITY GRADIOMETER REVIEW

Book 3

Review of GGSS Program Activity for 1984

Air Force Academy

Report No. 6501-927078 • FEBRUARY 12 - 13, 1985

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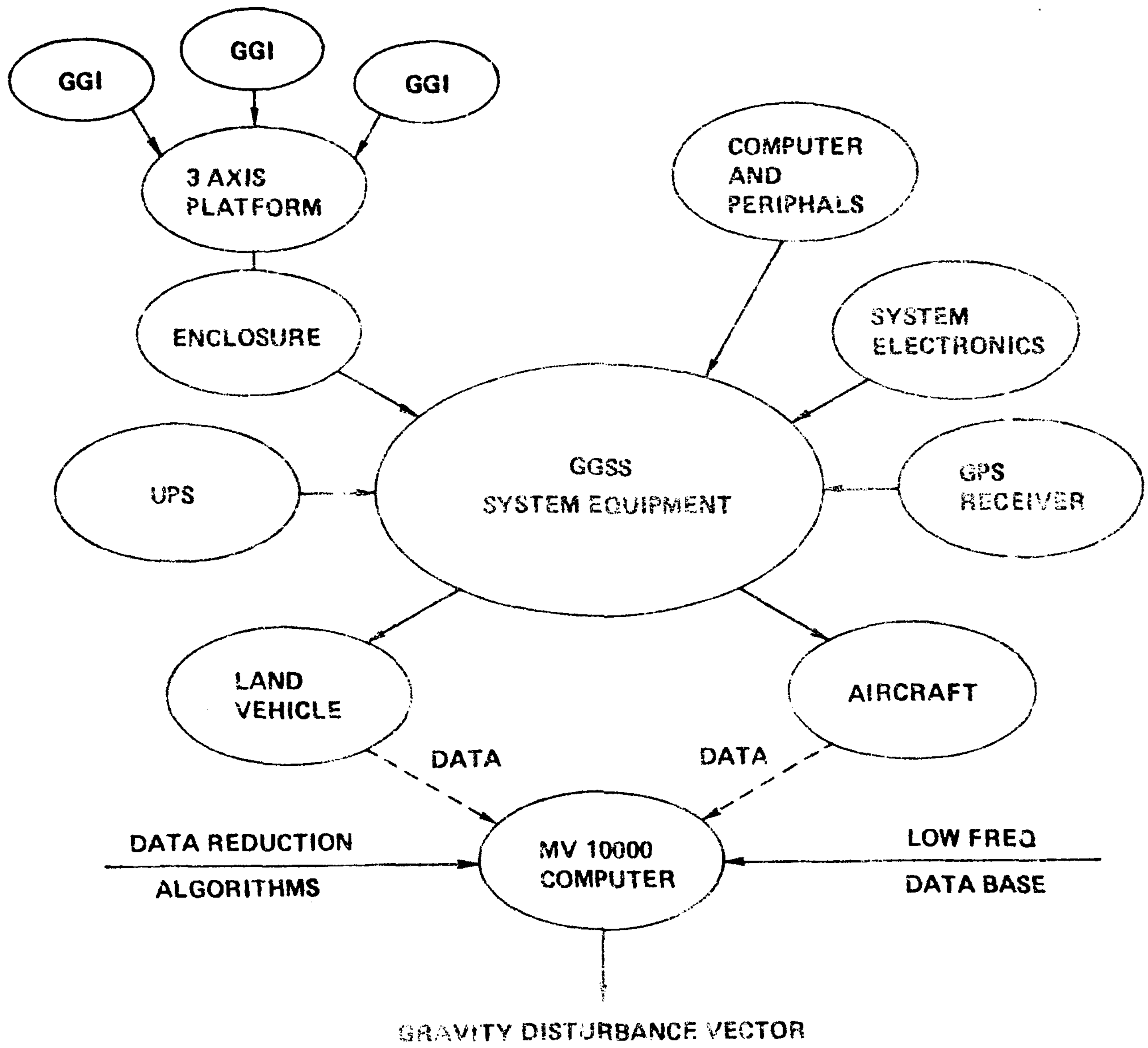
System Equipment



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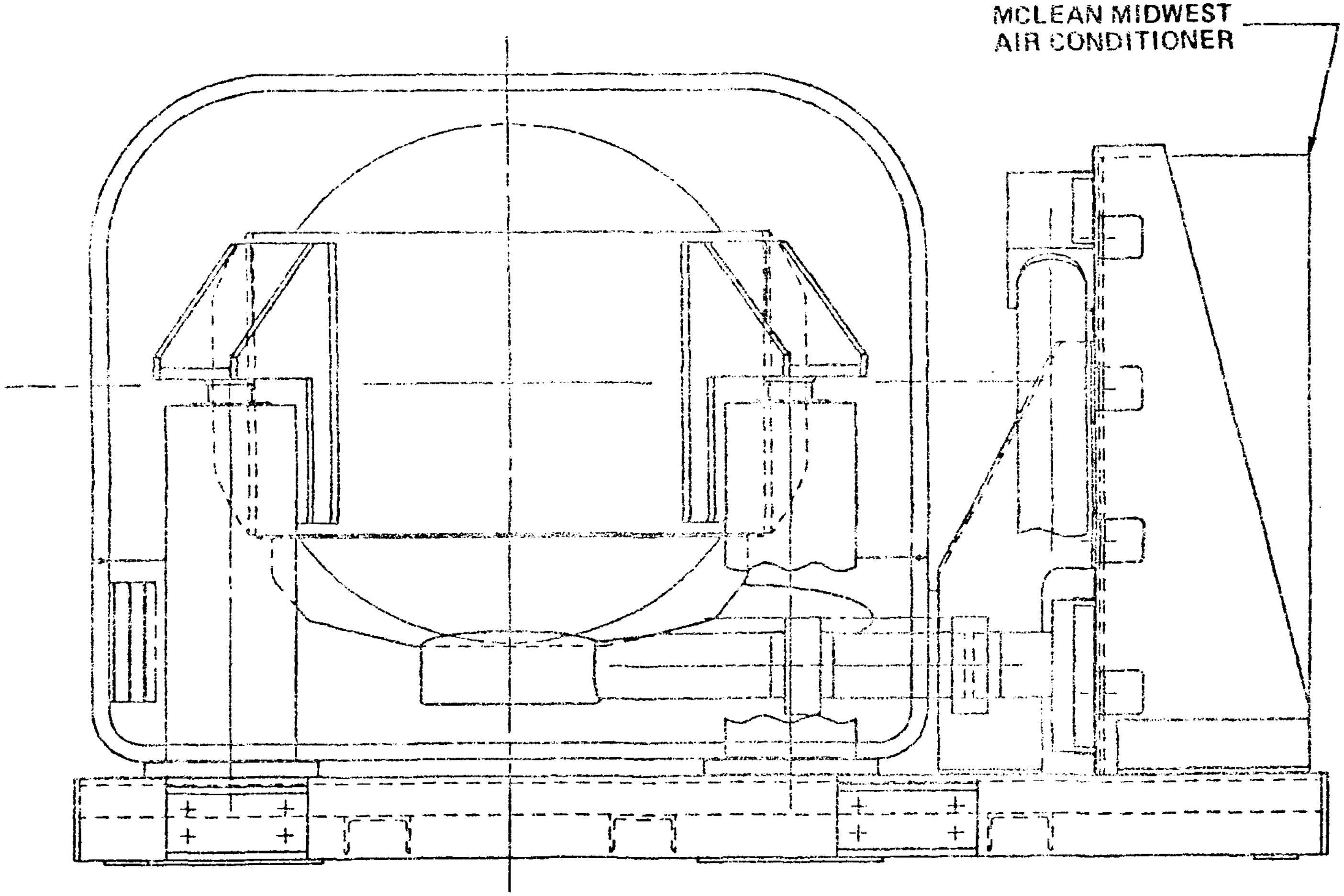
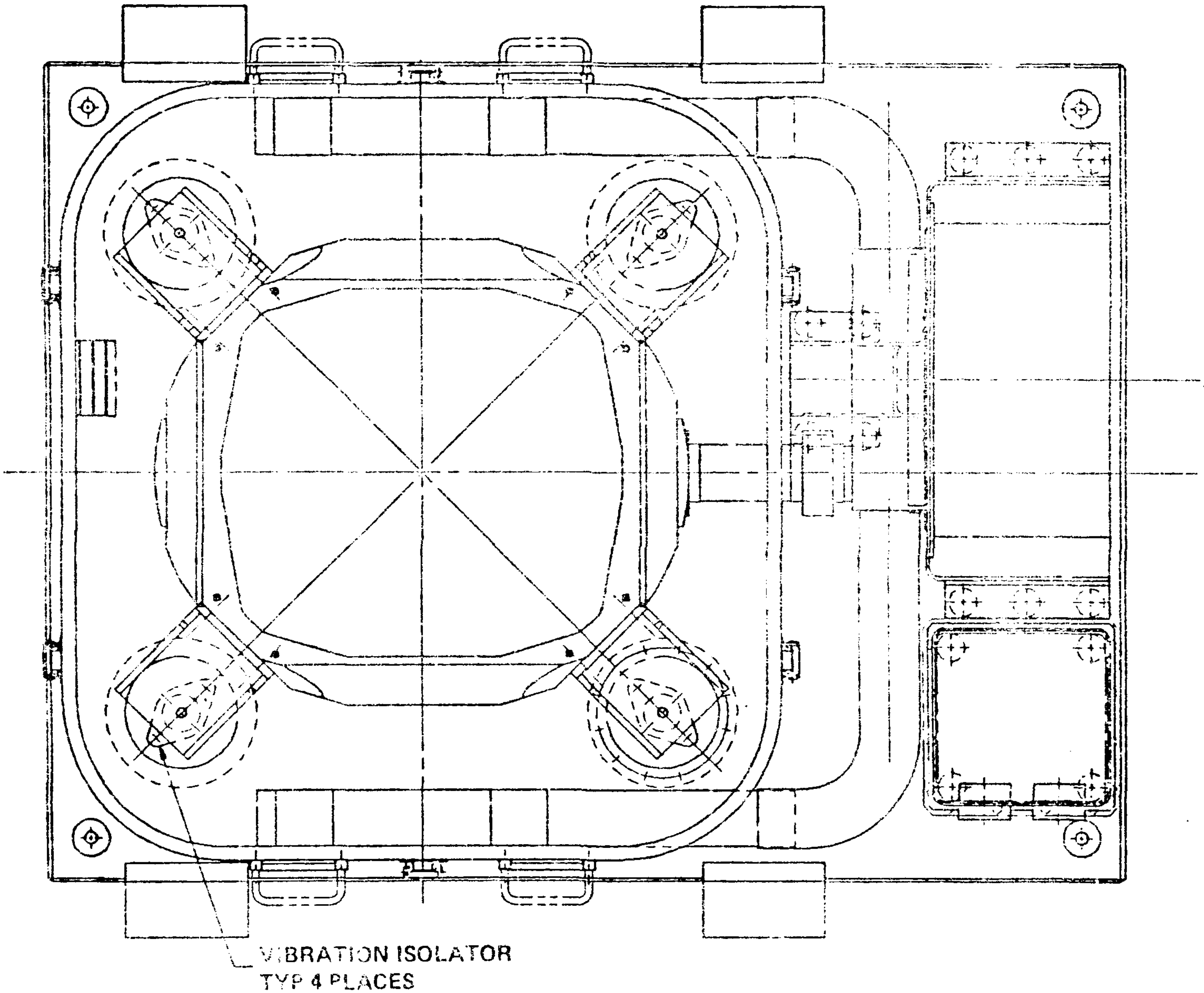
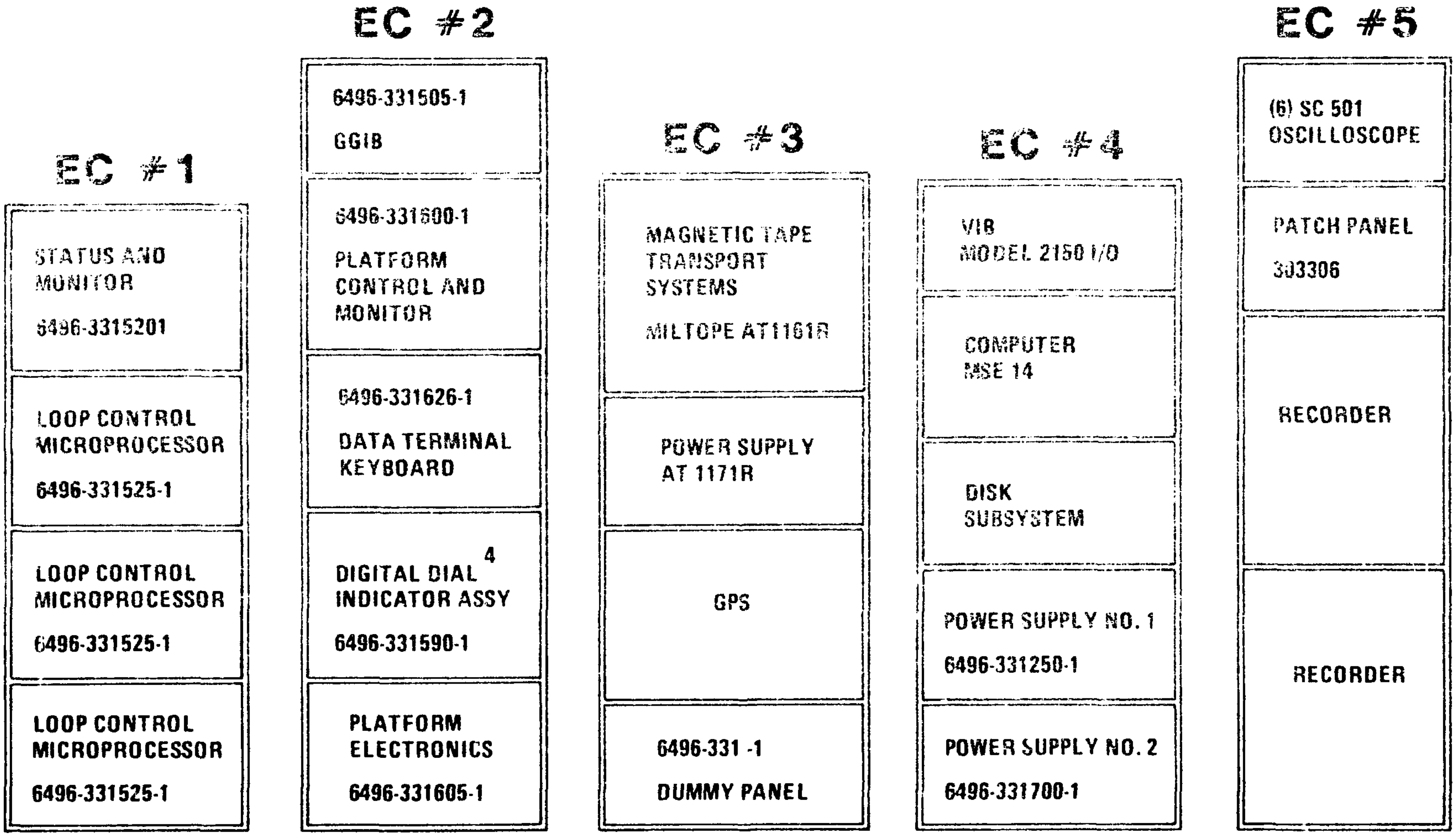
PLATFORM & ENCLOSURE - SIDE VIEW



PLATFORM & ENCLOSURE - TOP VIEW




EC #1
STATUS AND MONITOR
6496-3315201
LOOP CONTROL MICROPROCESSOR
6496-331525-1
LOOP CONTROL MICROPROCESSOR
6496-331525-1
LOOP CONTROL MICROPROCESSOR
6496-331525-1
EC #2
6496-331505-1
GGIB
6496-331600-1
PLATFORM CONTROL AND MONITOR
6496-331626-1
DATA TERMINAL KEYBOARD
DIGITAL DIAL INDICATOR ASSY
4
6496-331590-1
PLATFORM ELECTRONICS
6496-331605-1
EC #3
MAGNETIC TAPE TRANSPORT SYSTEMS
MILTOPE AT1161R
POWER SUPPLY AT 1171R
GPS
6496-331 -1
DUMMY PANEL
EC #4
VIB MODEL 2150 I/O
COMPUTER MSE 14
DISK SUBSYSTEM
POWER SUPPLY NO. 1
6496-331250-1
POWER SUPPLY NO. 2
6496-331700-1
EC #5
(6) SC 501 OSCILLOSCOPE
PATCH PANEL
303306
RECORDER
RECORDER

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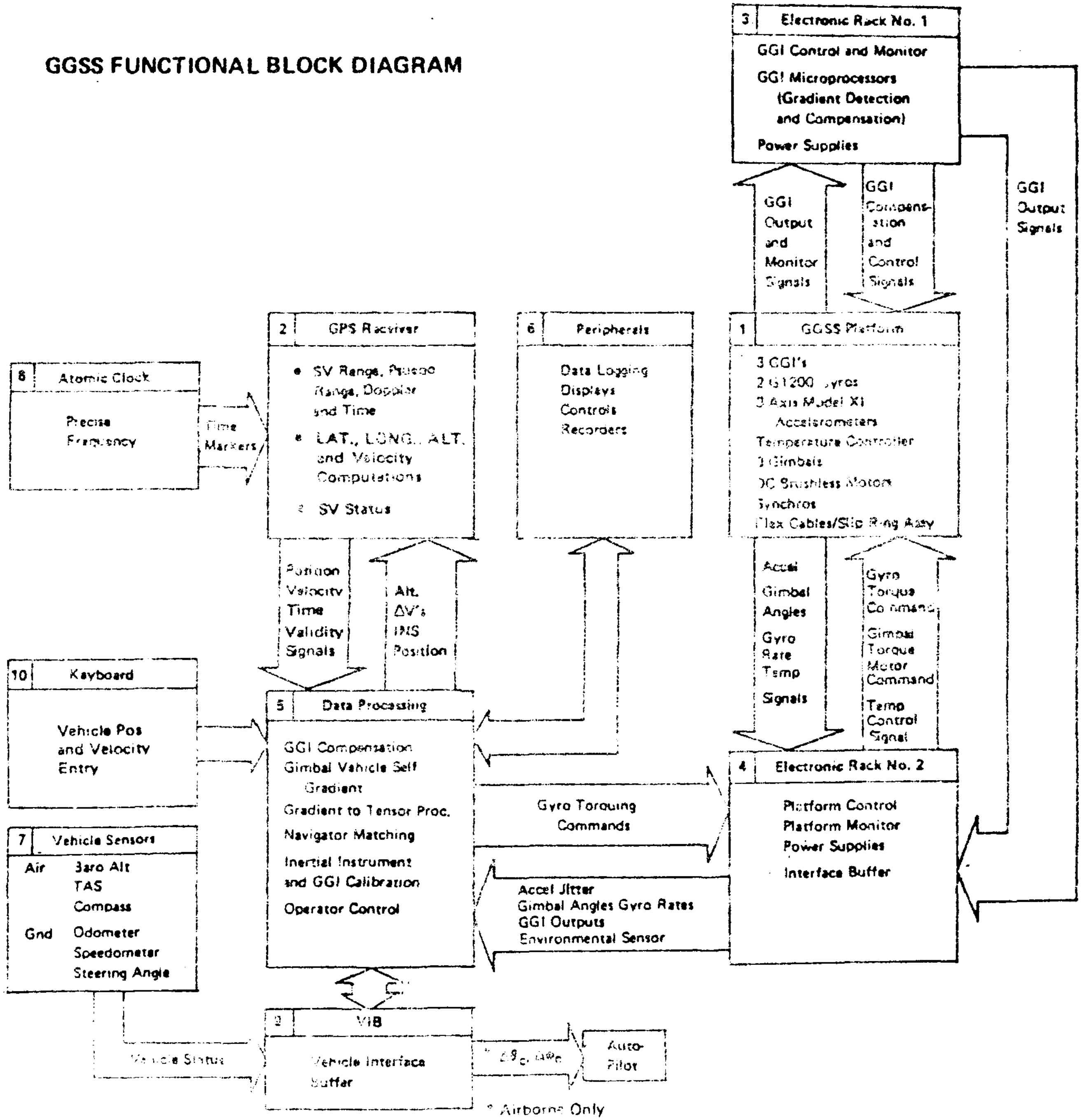
GGSS FUNCTIONAL BLOCK DIAGRAM



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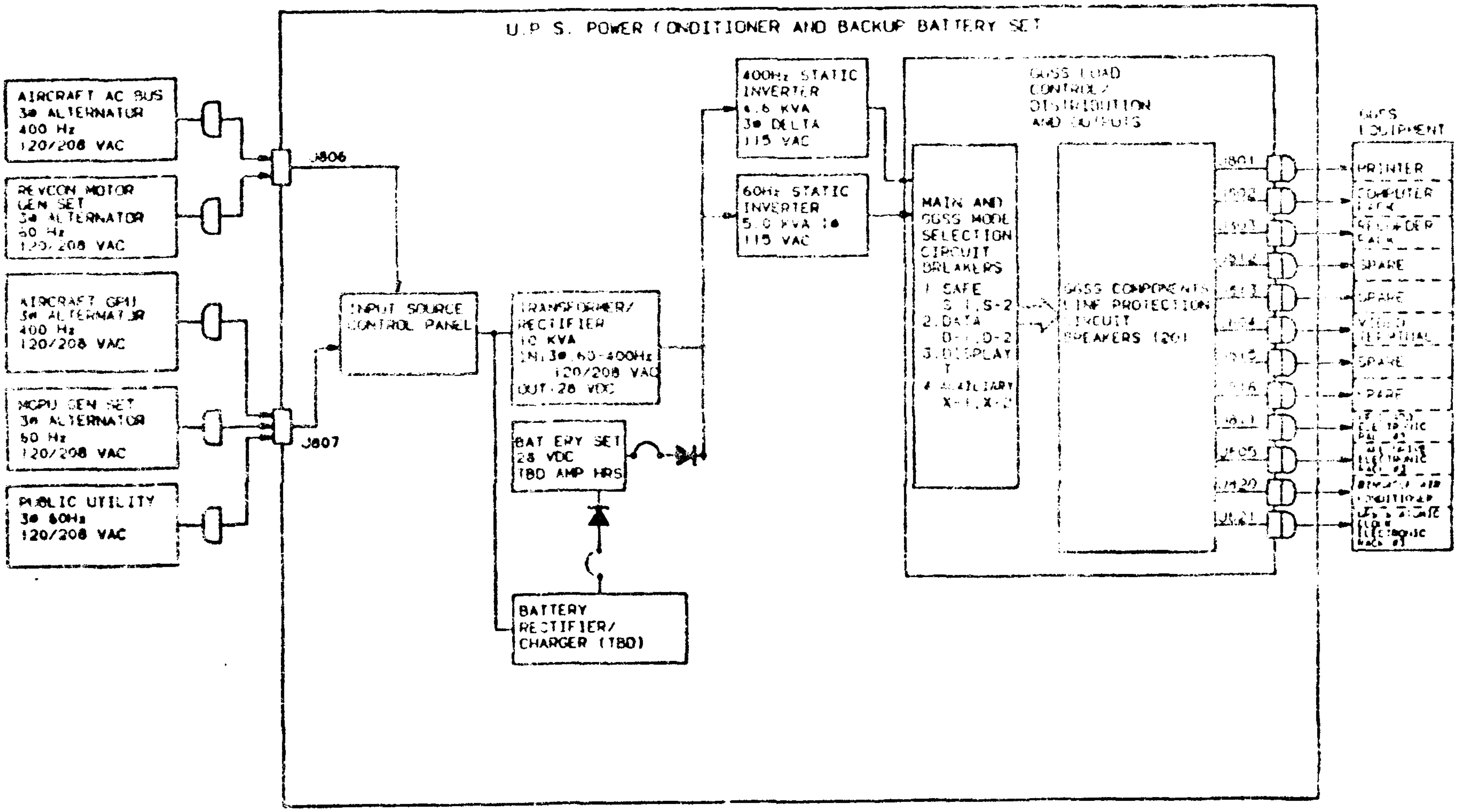
System Installations

GGS UNINTERRUPTABLE POWER SUPPLY (UPS)



Current Program Status

CURRENT PROGRAM STATUS

- HARDWARE
  - RACKS FABRICATION 75% COMPLETE
  - PLATFORM FABRICATION 30% COMPLETE
  - GGI S/N BUILT AND IN TEST
  - GGI S/N's 2 THRU 5 – ALL PURCHASE PARTS IN, FABRICATION OF SUB ASSY's STARTED

- MAJOR SUBCONTRACTED ITEMS
  - ROLM MSE/14 COMPUTER RECEIVED AN IN USE AS SGS
  - GPS RECEIVER IN AND CHECKED OUT
  - LITTON G-1200 GYROS ABOUT TO BE SHIPPED
  - UPS CONSOLE: PROPOSALS/QUOTES IN, WILL BE ON ORDER SOON
  - REYCON VEHICLE QUOTATION IN WORK; EXPECT MAY/JUNE '85 DELIVERY

- SOFTWARE
  - [illegible]ATIONAL PROGRAM 100% CODED (FORTRAN 77). FINAL CHANGES TO PPS AND [illegible]

    [illegible]

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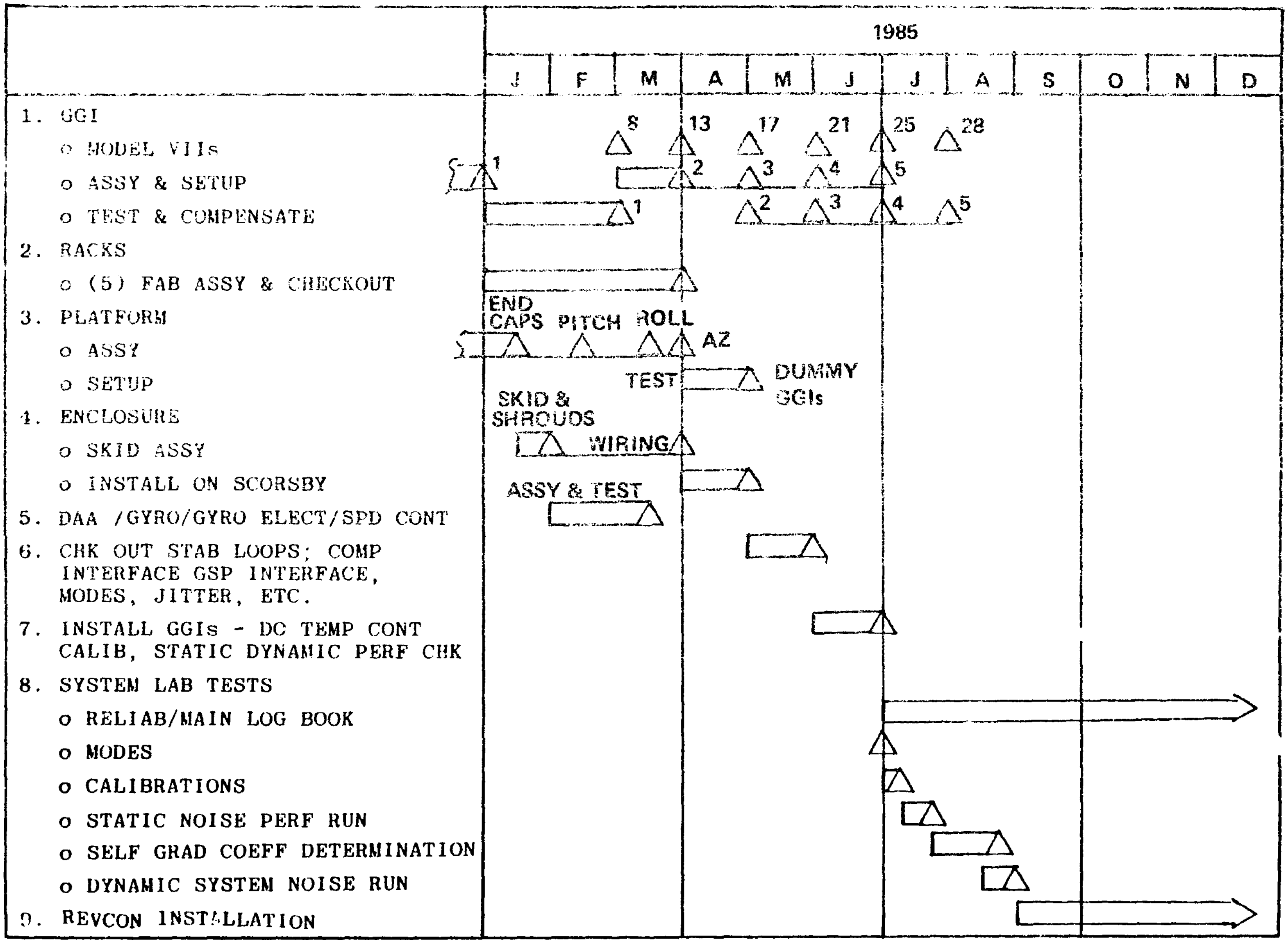
GGSS PROGRAM SCHEDULE



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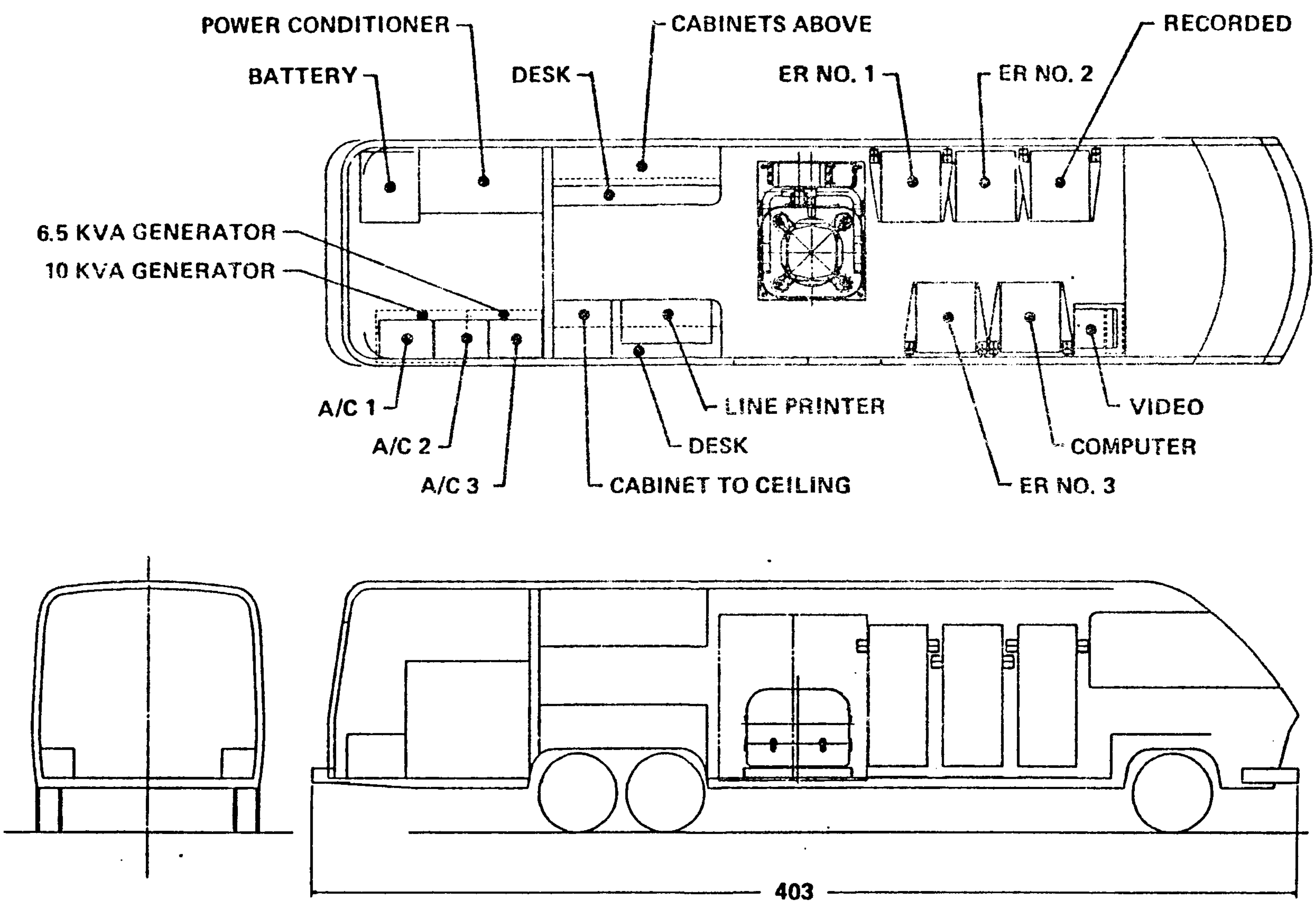
The Vehicles

LAND VEHICLE INSTALLATION



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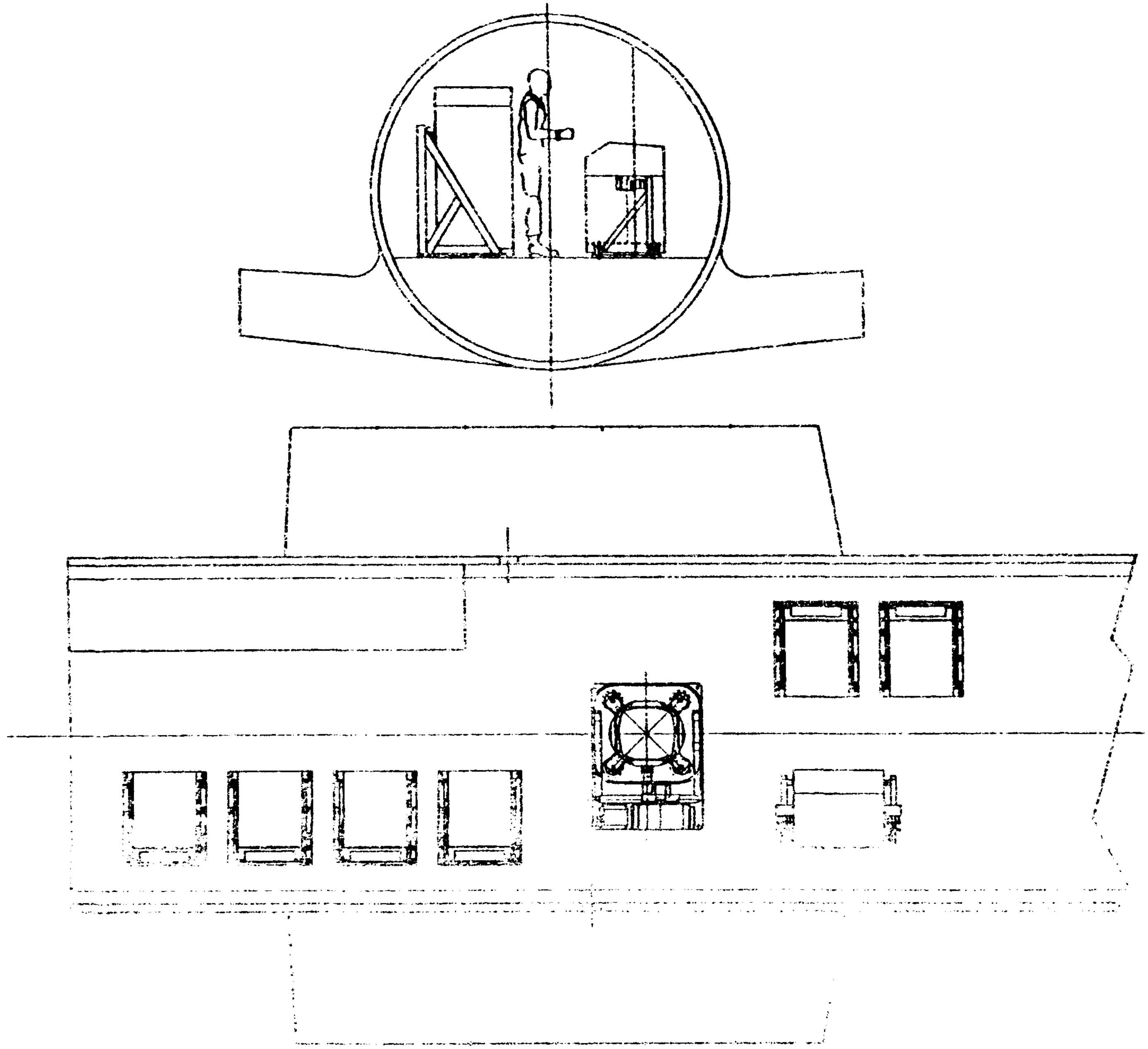
P-3 INSTALLATION

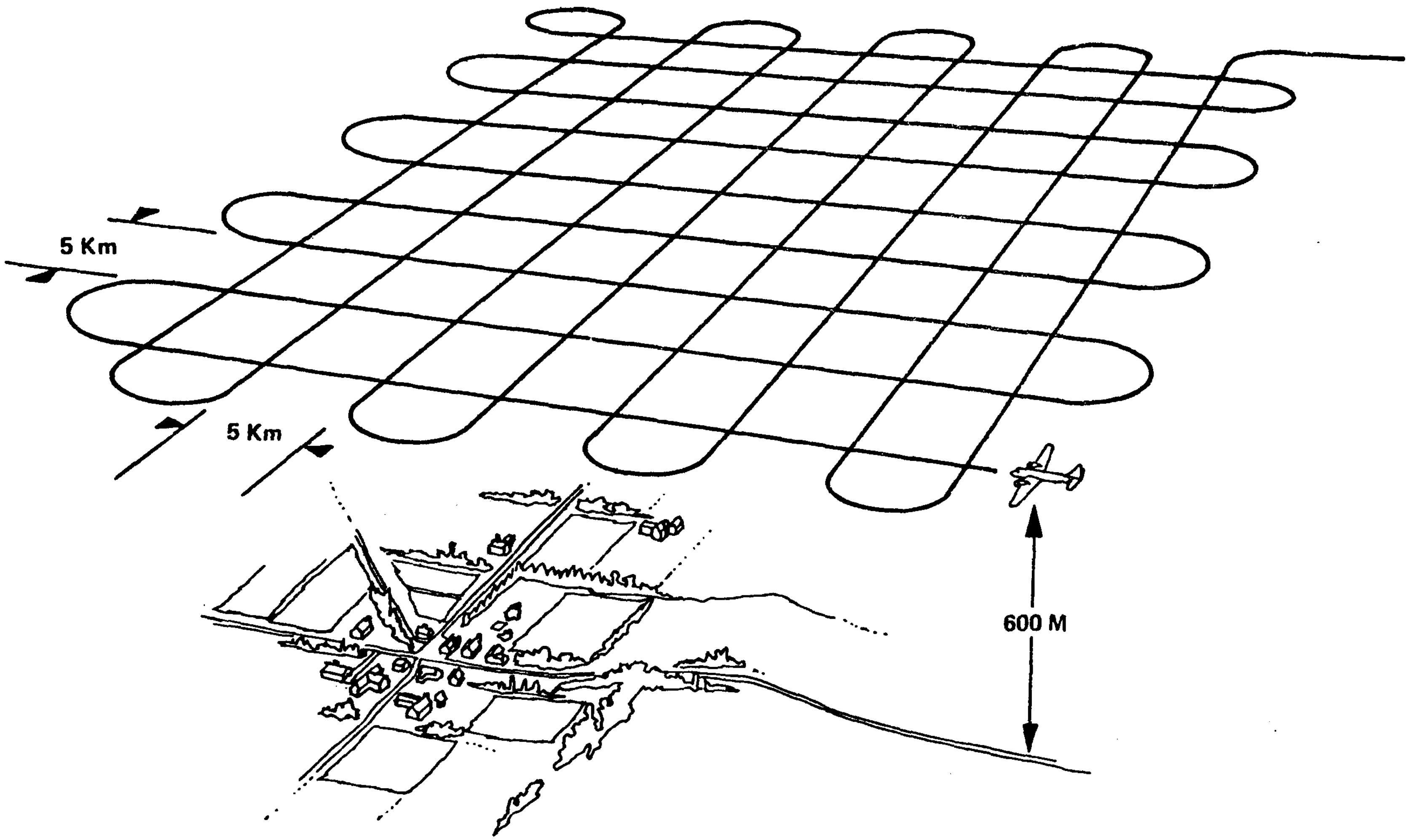


The Mission

GGSS OBJECTIVE

Measure Elements of Gravity Gradient Tensor Onboard Aircraft or Landvehicle and Determine Gravity Disturbance Vector by Postmission Smoothing Analysis Under Following Conditions.

	Aircraft	Landvehicle
Speed (KM/HR)	300	30 to 90
Maximum Wavelength (KM)	500	NA
Maximum Track Length (KM)	NA	200 KM
Altitude Above Terrain (M)	600	0
Track Spacing (KM)	5	NA
Deflection Survey Accuracy (Arc Sec)	0.18	0.18
Vertical Component Accuracy (mgal)	0.9	0.9


5 Km
5 Km
600 M

Test Plan

PHASE I LAND VEHICLE

- **OBJECTIVES**
  - ESTABLISH PERFORMANCE OF GGSS IN A MOVING LAND VEHICLE ENVIRONMENT.
  - CHARACTERIZE STATISTICALLY THE GRAVITY GRADIENT FIELD EXPERIENCED IN A LAND VEHICLE.

TEST METHOD

- USE THE GGSS TO IDENTIFY A $\approx$ 10 KM STRAIGHT SECTION OF ROAD;

  LEVEL, GRADIENT QUIET, LIGHT TRAFFIC

  SUITABLE OFF ROAD PARKING LOCATION NEAR EACH END

- USE GGSS UNDER GPS CONTROL WITH LV PARKED WITH FIXED HEADING AT EACH END POINT TO ESTABLISH END POINT POSITION COORDINATES AND GRADIENTS.

- CAROUSEL START AT ONE END OF TRACK DESIGNATED "BASE POINT".

- DRIVE TO OTHER END OF TRACK IN THE IG + O + MAP MODE AT THE DESIGNATED SPEED.

- AFTER PARKING SWITCH TO IG + ZV + KFP MODE REMAIN IN THIS MODE FOR 7 MINUTES.

- REPEAT UNTIL 6 TO 10 ROUND TRIPS ARE COMPLETED.

TEST METHOD CONT

- CAROUSEL END.
- CONDUCT QUICK LOOK ASSESSMENT OF TEST.
- REPEAT TEST AT LV SPEEDS OF 30, 40, 50 KM/HR. CONDUCT ADDITIONAL SURVEYS TO CHARACTERIZE TYPICAL LV GRADIENT SIGNAL.
  - TEST ROAD STRUCTURE SIGNAL BY STATIC MEASUREMENTS FROM EDGE-TO-EDGE ACROSS SEVERAL TYPICAL ROADS.
  - CONDUCT SURVEY THROUGH BOSTON HILLS SOUTH OF BUFFALO.
  - CONDUCT SURVEYS OVER TRACK CROSSINGS, UNDERPASSES, etc.

CAROUSEL START/END

- AT START OF TEST; VEHICLE, LAND OR AIR, IS PARKED WITH A FIXED HEADING AT A BASE POINT WITH A FIXED DISPOSITION OF SUPPORT EQUIPMENT AND A FIXED REPEATABLE FUEL LOAD.
- DISPLAY GYRO CALIBRATION PARAMETERS BIAS & SCALE FACTOR.
- START MISSION TAPE RECORDING.
- RUN IN CAROUSEL MODE FOR ONE CAROUSEL ROTATION (500 DEG/HR) WHILE OPERATING IN THE IG + ZV + KFP MODE RETRIM GYRO BIASES AND SCALE FACTORS.
- DISPLAY NEW VALUES OF GYRO CALIBRATION.
- TAPE RECORDED GGI OUTPUTS DURING CAROUSEL WILL BE REDUCED POST MISSION TO CONTROL SOME GGI BIASES.
- SWITCH TO NED MODE & PROCEED WITH MISSION.
- REFUEL AT END OF MISSION AND REPEAT ABOVE PROCEDURE.

QUICK LOOK ROLM COMPUTER

- INSPECT IN FLIGHT STRIP CHART RECORDINGS OF BUTTERWORTH FILTERED GGI OUTPUTS, ΣI_i, PLATFORM CONTROL SIGNALS.
- READ MISSION TAPE PLOT TO STRIP CHART OTHER VARIABLES. δLAT, δLON, δALT, δV_N, δV_E, δV_D, GIMBAL ANGLES, A_N, A_E, A_D, ETC.
- BASED ON CAROUSEL START/END DATA.
  - CHECK HISTORY OF GYRO BIAS AND SCALE FACTOR CALIBRATION FOR REASONABLENESS.
  - CHECK HISTORY OF GGI BIAS AND DRIFT FOR REASONABLENESS.
- GENERATE PSDs OF 3 GGI MODULATED OUTPUTS ONE AVERAGE PSD FOR EACH 30 MIN.
- PSD OF ΣI_i.

GGI PERFORMANCE MONITOR
(PROPOSED BY A. ZORN, DRC)

IN LINE OUTPUTS OF ANY ORTHOGONAL SET OF 3 GGIs ARE:

$$I_1 = \frac{W_{33} - W_{22}}{2} + \frac{\omega_3^2 - \omega_2^2}{2} + N_1 + B_1 + D_1 T + F_1(\underline{a})$$

$$I_2 = \frac{W_{11} - W_{33}}{2} + \frac{\omega_1^2 - \omega_3^2}{2} + N_2 + B_2 + D_2 T + F_2(\underline{a})$$

$$I_3 = \frac{W_{22} - W_{11}}{2} + \frac{\omega_2^2 - \omega_1^2}{2} + N_3 + B_3 + D_3 T + F_3(\underline{a})$$

$$\Sigma I_i = \Sigma N_i + \Sigma B_i + T \Sigma D_i + \Sigma F_i(\underline{a})$$

ANALYSIS/EVALUATION MV10000

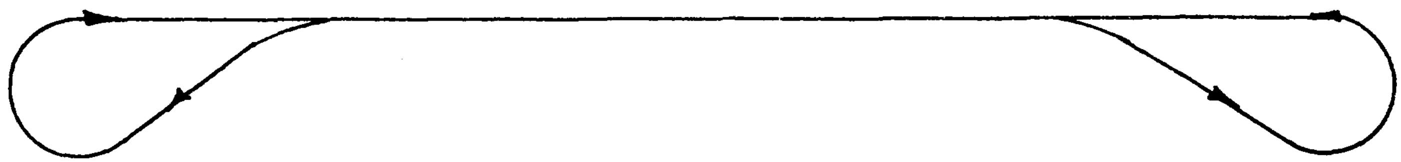
- ADJUST ALONG TRACK POSITION POST MISSION BASED ON POSITION ERROR AT END OF EACH TRACK.
- STAGE I POST MISSION PROCESSING YIELDS 6 GGI OUTPUTS 1/SEC RATE IN GGI FRAME.
- COMPARE OUTPUT WITH THOSE OF STATIC SURVEY AND THOSE AT OTHER LV SPEEDS.
- OBTAIN BEST ESTIMATE OF SIGNAL BASED ON AVAILABLE DATA. (TRACK AVERAGES OR STATIC READINGS).
- FOR EACH TEST (6-10 TRACKS AT DESIGNATED SPEED) COMPUTE RESIDUAL ERROR TIME HISTORY AND CORRESPONDING ACF AND PSD.
- ASSESS REQUIREMENT FOR POST MISSION ACCELERATION COMPENSATION.

PHASE I AIRBORNE

- **OBJECTIVE**
  - ESTABLISH PERFORMANCE OF GGSS IN AN AIRCRAFT UNDER VARIOUS CONDITIONS OF SPEED, ALTITUDE TURBULENCE, FLIGHT CONTROL, ETC.

TEST METHOD PHASE I A/B

- CAROUSEL START.
- UNDER GPS CONTROL FLY 6 TO 10 ROUND TRIPS ON A STRAIGHT TRACK ≈ 90 KM LONG.



- ENTER FIRST TRACK AT DESIGNATED GROUND SPEED (TO 5%) AT DESIGNATED ALTITUDE.
- FLY PRESSURE ALTITUDE (NO IN FLIGHT RESETTING).
- ADJUST GROUND SPEED AFTER EACH TURN.
- RETURN TO BASE.
- CAROUSEL END.
- QUICK LOOK ASSESSMENT OF DATA
- CONDUCT 4 TESTS AT ALTITUDES 600M & 1200M AT 300 & 350 KM/HR.

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ANALYSIS/EVALUATION PHASE I A/B MV10000

- USE STAGE I DATA PROCESSING.
- USE CAROUSEL START-END CLOSURE TO ESTABLISH 6 GGI OUTPUT DRIFT RATES AND BIASES.
- DETERMINE SIGNAL ALONG TRACK.
- COMPUTE TIME HISTORY OF RESIDUAL ERROR.
- COMPUTE ACF & PSD OF RESIDUAL ERROR.
- ASSESS REQUIREMENT FOR ACCELERATION COMPENSATION.

PHASE II LAND VEHICLE

- **OBJECTIVE**
  - DEMONSTRATE GGSS ABILITY TO TRANSFER DISTURBANCE VECTOR ALONG A ROUTE CONNECTING END POINTS WHERE THE DISTURBANCE VECTOR IS KNOWN. GOAL IS .18 $\widehat{\text{SEC}}$ AND .9 MGAL AT THE MIDPOINT.

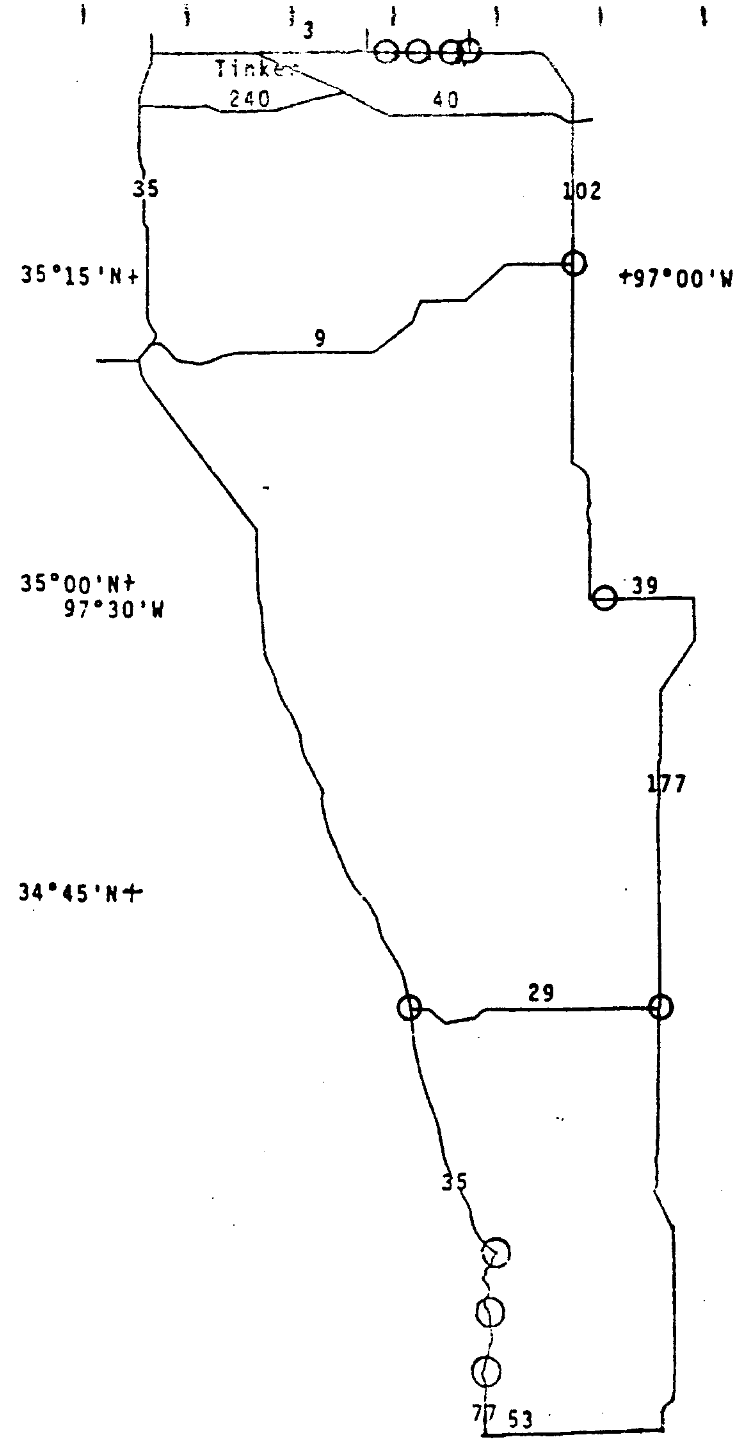
TEST METHOD PHASE II LV

- DMA HAS PLANNED 4 TESTS DESIGNATED A THROUGH D IN THE TEST AREA RANGING UP TO ≈ 340 KM IN LENGTH AND EACH ENCOUNTERING MORE RUGGED TERRAIN. ASTROGEODETIC SURVEY POINTS HAVE ALSO BEEN DESIGNATED ALONG THESE ROUTES.
  - CAROUSEL START
  - CONDUCT TEST UNDER GOOD GPS CONTROL. REVERT TO IG + OHP OR IG + ZV MODE UNTIL GPS COVERAGE IS REESTABLISHED.
  - CAROUSEL START.
  - TRAVEL IN IG + GPS MODE AT SELECTED SPEED.
  - PARK AND SWITCH TO IG + ZV + GPS MODE FOR 5 MINUTES AT EACH ASTROGEODETIC POINT.
  - USE IG + PRESSURE ALTIMETER + GPS VERTICAL.
  - CAROUSEL END.
  - QUICK LOOK.

ANALYSIS PHASE II LV MV10000

- USE STAGE I PROCESSING YIELDING 1 SEC SAMPLES OF 6 GGI OUTPUTS IN GGI COORDINATES.
- USE CAROUSELS START/END DATA TO ESTIMATE GGI BIASES AND DRIFTS.
- USE TIE POINTS AND CORRECTED GRADIOMETER MEASUREMENTS TO ESTIMATE THE DISTURBANCE VECTOR ALONG THE ROUTE.
- GENERATE ERROR STATISTICS AT TRUTH DATA POINTS.
- IN THE POST MISSION REDUCTION, EACH ASTROGEODETIC POINT CAN BE ARBITRARILY DESIGNATED AS TIE POINTS OR TRUTH DATA POINTS, THUS MULTIPLYING THE MISSION BASE.

GRAVITY GRADIOMETER SURVEY SYSTEM
PHASE 2 LAND TEST (1-30 APRIL 1986)
TEST D



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PHASE II AIRBORNE

- **OBJECTIVE**
  - FOR

    600M A/C ALTITUDE

    5 KM TRACK SPACING ORTHOGONAL TRACKS

    315 KM SQUARE SURVEY AREA

    - DEMONSTRATE GGSS PERFORMANCE CONSISTENT WITH .18 SEC DEFLECTION & .9 MGAL GRAVITY DISTURBANCE FOR WAVELENGTHS SHORTER THAN 500 KM.
  - VALIDATE DATA REDUCTION PROCEDURE
  - VALIDATE FIELD MODEL IN THE TEST AREA

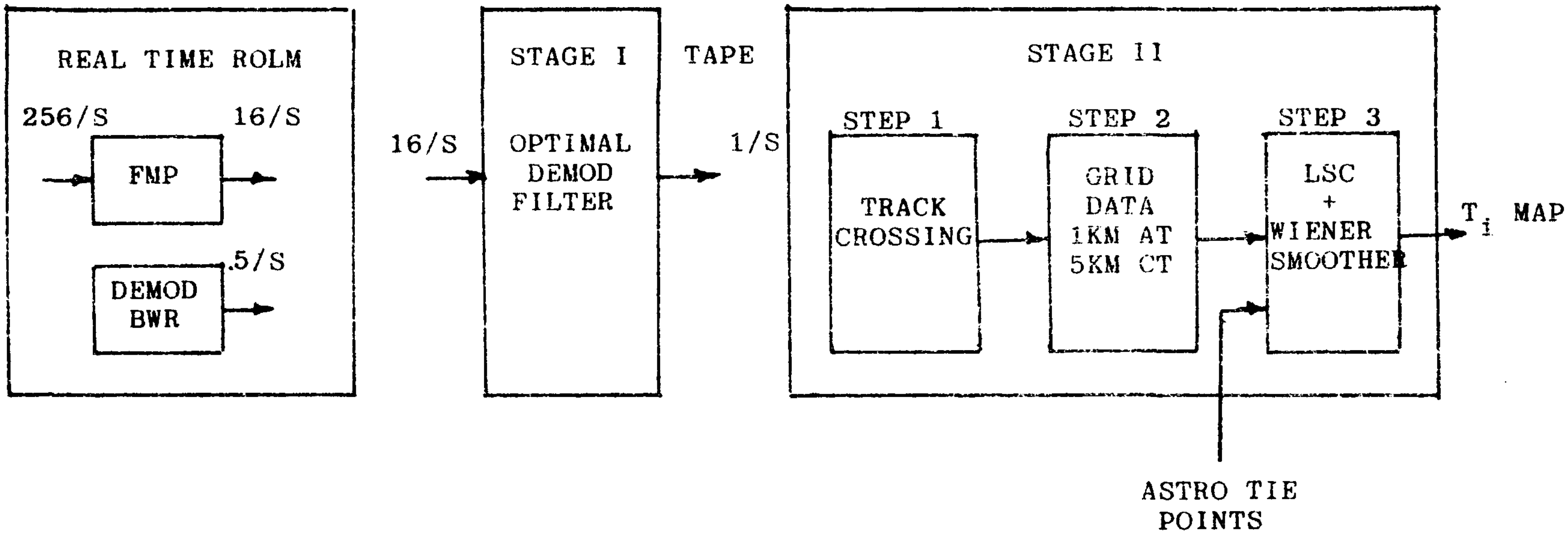
TEST METHOD PHASE II AIRBORNE

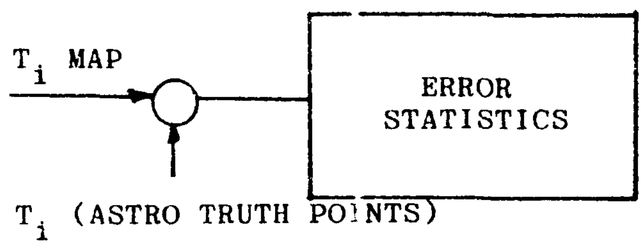
- PRELIMINARY ISSUES
  - 315 KM SQUARE TO BE SURVEYED.
    - LOCATION, ORIENTATION, ALTITUDE
    - DEFINITION OF MAP PROJECTION FROM GEOGRAPHIC TO FLAT GRID. (AUTOPILOT STEERING IMPLICATIONS)
    - CONSTANT GROUND SPEED
  - ASTROGEODETIC SURVEY POINTS SERVE TWO RULES
    - TRUTH DATA POINTS
    - TIE POINTS USED TO CONTROL LOW FREQUENCY
  - MISSION PLANNING CONSIDERATIONS
    - GPS COVERAGE, TURBULENCE
    - ≈ 5 TO 6 TRACKS EACH MISSION 315 KM LONG
      - ALL IN ONE DIRECTION 5, 10, 15 KM TRACK SPACING
    - ALTERNATE DIRECTIONS ON ALTERNATE MISSIONS
    - CONSTANT GROUND SPEED AT 350 KM/HR PROVIDES SAFE MARGIN FOR AIR SPEED.
    - FLY BAROMETRIC ALTIMETER HOLD (NO RESETTING IN FLIGHT)

TEST METHOD (CONT) PHASE II AIRBORNE

- MISSION SCENARIO
  - CAROUSEL START
  - IG + GPS MODE, NED
  - ADJUST GROUND SPEED AFTER EACH TURN (5%)
  - GPS OUTAGE STRATEGY
  - NOTE ALL EVENTS WITH EVENT MARKER
  - AFTER LAST TRACK RETURN TO BASE ALONG SAME LEG FLOWN OUT.
  - CAROUSEL END
  - QUICK LOOK

ANALYSIS PHASE II AIRBORNE MV10002





Bell Aerospace TEXTRON

GGSS DATA ANALYSIS (REVIEW)

by AFGL 12 FEB 85

BELL AEROSPACE	-	PRIMARY RESPONSIBILITY
TASC	-	INDEPENDENT ANALYSIS
NSWC	-	GRAVITY MODEL
DATA ANALYSIS WORKING GROUP (D.A.W.G.)	-	COORDINATION

STAGE II DATA PROCESSING

LAND VEHICLE TEST

$$T_j(P_2) = T_j(P_1) + \int_{P_1}^{P_2} \left(T_{jx}\, dx + T_{jy}\, dy + T_{jz}\, dz \right), \quad j = x, y, z$$

AIRBORNE TEST

DOWNWARD CONTINUATION	-	BOUNDARY-VALUE PROBLEM NUMERICAL INSTABILITY
LARGE DATA SET	-	DIFFICULT DATA PROCESSING
INCOMPLETE DATA SET	-	FINITE EXTENT & ALIASING ERRORS

OPTIMAL ESTIMATION

LEAST-SQUARES COLLOCATION

NON-, SUB-OPTIMAL ESTIMATION

INTEGRAL FORMULAS

SPACE DOMAIN L.S.C. APPROXIMATION

FREQUENCY DOMAIN L.S.C. APPROXIMATION

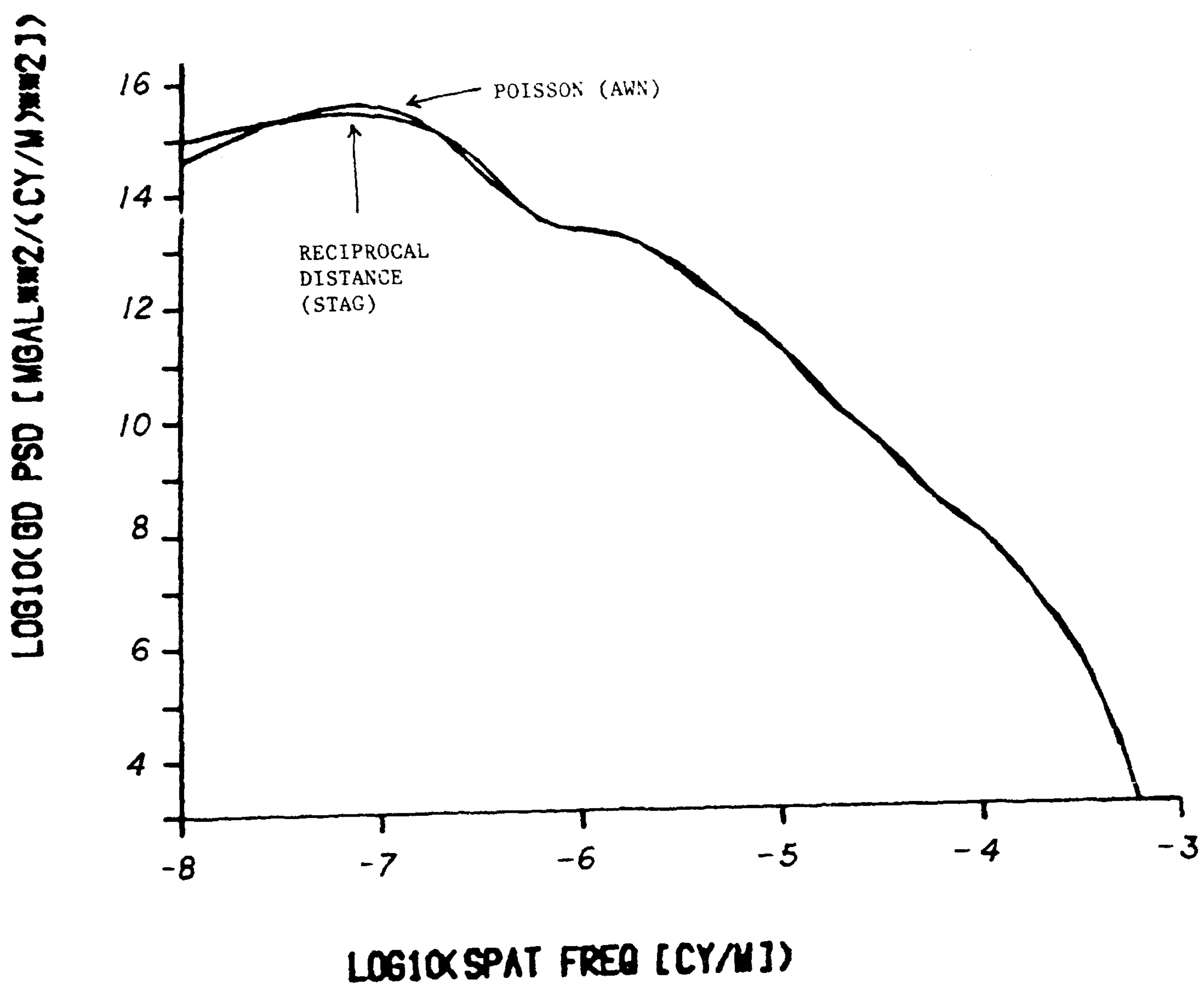


Figure 1: Gravity Disturbance (GD) power spectral densities for GGSS Phase II test area.

SP-4423-16

GRAVITY GRADIOMETER (GGSS) TEST PLANNING AND TEST DATA TREATMENT

12-13 FEBRUARY 1985

Prepared for:

THIRTEENTH MOVING BASE GRAVITY GRADIOMETER REVIEW
United States Air Force Academy
Colorado

Prepared by:
W.G. HELLER

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Reading, Massachusetts 01867

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ABSTRACT

GGSS TEST PLANNING AND TEST DATA TREATMENT

W.G. HELLER

TASC IS RESPONSIBLE FOR INDEPENDENT EVALUATION OF THE GGSS, TEST AND SURVEY PLANNING, DATA REDUCTION ALGORITHMS, AND OTHER ISSUES RELATING TO GGSS DEVELOPMENT. DISCUSSED IN THIS PRESENTATION ARE TECHNICAL FACTORS DRIVING THE DESIGN OF THE AIRBORNE TEST PROGRAM, TEST-BASED VALIDATION OF GGSS PERFORMANCE AND DATA COLLECTION SCENARIOS. THESE ISSUES ARE RELATED TO OUR KNOWLEDGE OF THE GRAVITY FIELD IN THE NORTH TEXAS TEST AREA AND INFERENCES ARE DRAWN ABOUT LIKELY ACCURACY WHICH THE GRADIOMETER WILL ACHIEVE THERE. A SUMMARY PERSPECTIVE OF THE NEAR FUTURE OF MOVING BASE GRADIOMETRY IS OFFERED.

A 20758

OVERVIEW

- TASC'S ROLE
- REVIEW OF TECHNICAL FACTORS DRIVING GGSS TEST DESIGN
- PERFORMANCE VALIDATION OF THE GGSS
- DATA COLLECTION SCENARIOS
- GRAVITY FIELD IN THE NORTH TEXAS TEST AREA
- IMPLICATIONS OF TEST AREA GRAVITY ON GGSS PERFORMANCE
- SUMMARY PERSPECTIVE

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TASC'S INDEPTNDENT ANALYSIS RESPONSIBILITIES

- QUANTITATIVE UNDERSTANDING OF GGSS ERRORS AND THEIR IMPLICATIONS
- TEST AND SURVEY PLANNING
- DATA ANALYSIS ALGORITHM DEVELOPMENT
- INITIALIZATION, CALIBRATION AND USE OF ANCILLARY GRAVITY DATA

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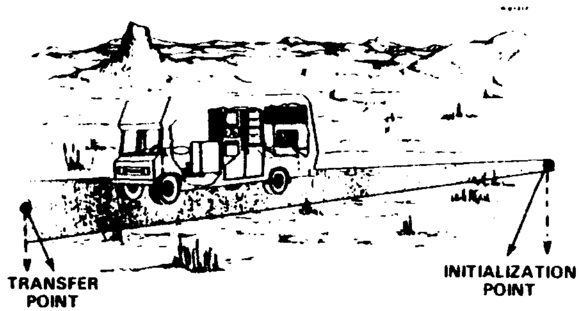
PLANNED TEST SEQUENCE

GOALS



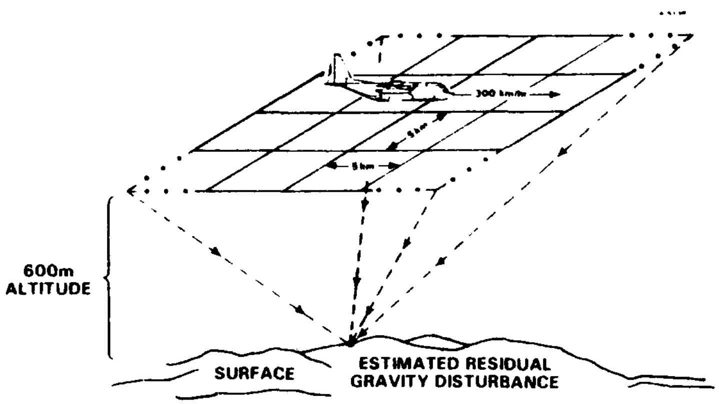
SURFACE TESTING

DEMONSTRATE GGSS UNDER NON-LABORATORY MOVING BASE CONDITIONS

PERFORM SHAKEDOWN OPERATIONS

PROVIDE DATA TO

- ESTABLISH PRELIMINARY ERROR MODELS
- PROVE CAPABILITY TO TRANSFER VERTICAL DEFLECTIONS



AIRBORNE TESTING

CONFIRM THAT GGSS ERRORS ARE WITHIN BUDGET RANGE

DEMONSTRATE GRAVITY DISTURBANCE VECTOR RECOVERY

VERIFY PERFORMANCE vs SPECIFICATIONS

- $\delta g_z \rightarrow 0.9$ mgal rms, $\lambda \leq 500$ km
- DOV $\rightarrow 0.18 \widehat{sec}$ rms, $\lambda \leq 500$ km

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KEY DIFFERENCES BETWEEN GGSS TEST AND SURVEY OPERATIONS

SURVEY

- USE GRADIOMETER DATA FROM SURVEY AREA
- USE EXISTING GRAVITY FIELD DATA BOTH INSIDE AND OUTSIDE OF SURVEY AREA
- <u>COMBINE</u> GRADIOMETER DATA AND OTHER DATA TO ESTIMATE <u>ENTIRE GRAVITY DISTURBANCE VECTOR</u>

TEST

- USE GRADIOMETER DATA *TAKEN IN TEST* AREA
- ESTIMATE "RESIDUAL" GRAVITY DISTURBANCE VECTOR WHICH CONTAINS ONLY SHORT GRAVITY WAVELENGTHS (IDEALLY, < 500 km)
- <u>WITHOLD</u> OTHER SOURCES OF SHORT WAVELENGTH GRAVITY FIELD INFORMATION FROM GGSS ESTIMATION PROCESS
- REMOVE LONG WAVELENGTH CONTENT FROM <u>TRUTH DATA WITHOUT INTRODUCING EXCESSIVE ERROR</u>
- <u>COMPARE</u> GGSS ESTIMATES OF RESIDUAL GRAVITY DISTURBANCE WITH TRUTH VALUES

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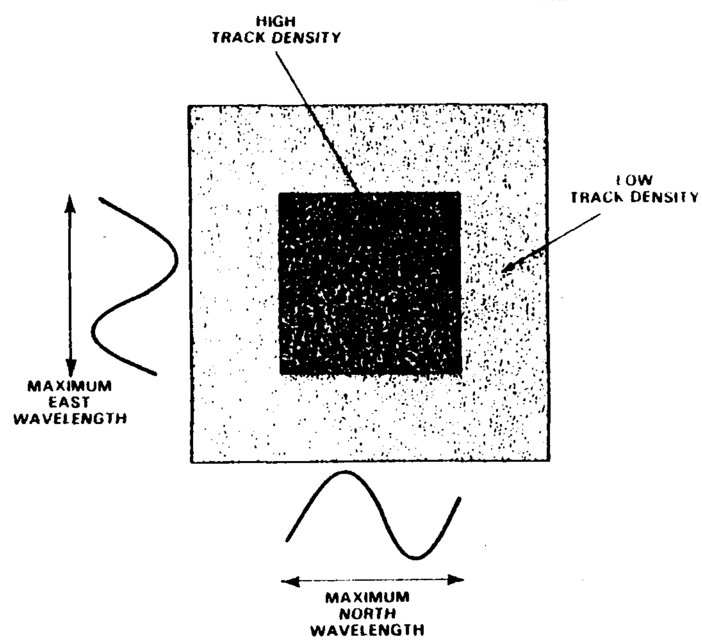
IMPLICATIONS OF LOCAL NATURE OF GRAVITY GRADIENT FIELD

- TEST GOAL IS TO ESTIMATE SURFACE RESIDUAL GRAVITY DISTURBANCE VECTOR FROM GRADIENT MEASUREMENTS ALOFT
- PROCESS REQUIRES GRADIENT DATA EXTENDING AWAY FROM ESTIMATION POINT
- IN PRACTICE, GRADIENT DATA EXTENT IS LIMITED TO SIZE OF SURVEY AREA
- "EDGE EFFECT" IS BUILT-IN TO AIRBORNE GGSS CONCEPT
- NECESSITATES LIMITING LONG WAVELENGTH TEST PERFORMANCE REQUIREMENT FOR THE GGSS
- GRAVITY VECTOR RECOVERY BEST AT WAVELENGTHS SHORTER THAN HALF TO 2/3 OF TEST AREA DIMENSION
- LOW DENSITY "COLLAR" AREA PROVIDES EFFICIENT MEANS TO EXTEND LONG WAVELENGTH RECOVERY



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TWO APPROACHES TO GGSS PERFORMANCE VALIDATION

- COMPARE DOWNWARD CONTINUED GRADIOMETER MEASUREMENTS WITH GROUND TRUTH DATA
  - COST OF FLIGHT HOURS MOTIVATES EXPERIMENTAL VERIFICATION OF GGSS AT WAVELENGTHS SOMEWHAT LESS THAN 500 km
  - ASTRO STATION COST AND LEAD-TIME REQUIREMENTS LIMIT VERTICAL DEFLECTION TRUTH DATA AVAILABILITY
  - EXISTING DATA BASE PROVIDES GOOD SOURCE OF VERTICAL GRAVITY DISTURBANCE TRUTH DATA
- MEASURE GGSS ERRORS ALONG REPEATED TRAVERSES OF SAME TRACK AND SIMULATE NOMINAL SURVEY AS DESCRIBED IN GGSS SPECIFICATIONS
  - VALIDATES PERFORMANCE vs SPECIFICATION FOR ENTIRE GRAVITY DISTURBANCE VECTOR
  - AVOIDS "STATISTICAL SIGNIFICANCE" PROBLEMS ASSOCIATED WITH LIMITED AREA OF COMPARISON
  - OBVIATES NEED FOR LARGE AMOUNTS OF TRUTH DATA
- BOTH APPROACHES ARE REQUIRED TO DEMONSTRATE SUCCESSFUL AIRBORNE GGSS PERFORMANCE

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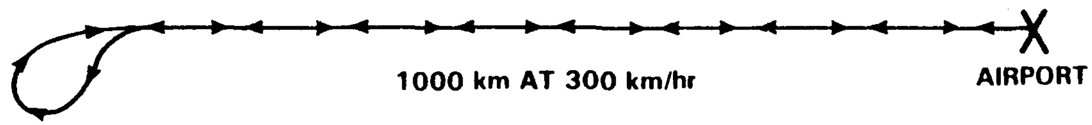
DATA COLLECTION TO DETERMINE GGSS SELF-NOISE

A 7676



- LONG TRACK IS FLOWN IN BOTH DIRECTIONS SEVERAL TIMES
- 1000 km LENGTH ADEQUATELY IDENTIFIES GGSS RED NOISE FOR NOMINAL AIRCRAFT VELOCITY
- NOMINAL GRADIENT FIELD ALONG FLIGHT PATH IDENTIFIED BY COMBINING DATA FROM ALL PASSES
- RESULTING GRADIENT ESTIMATES ARE SUBTRACTED FROM ORIGINAL DATA
- RESIDUAL NOISE IS USED TO COMPUTE GGSS ERROR SPECTRUM
- ERROR SPECTRUM IS USED TO DETERMINE PERFORMANCE vs SPECIFICATION BY SIMULATION
- LOGICAL INITIAL PHASE OF FLIGHT TESTING
  - 10 PASSES (5 EACH WAY) USE 35 FLIGHT HOURS
  - PROVIDES SUITABLE ERROR MODELS FOR NEXT PHASE (AREA COVERAGE) OF FLIGHT TEST DATA REDUCTION

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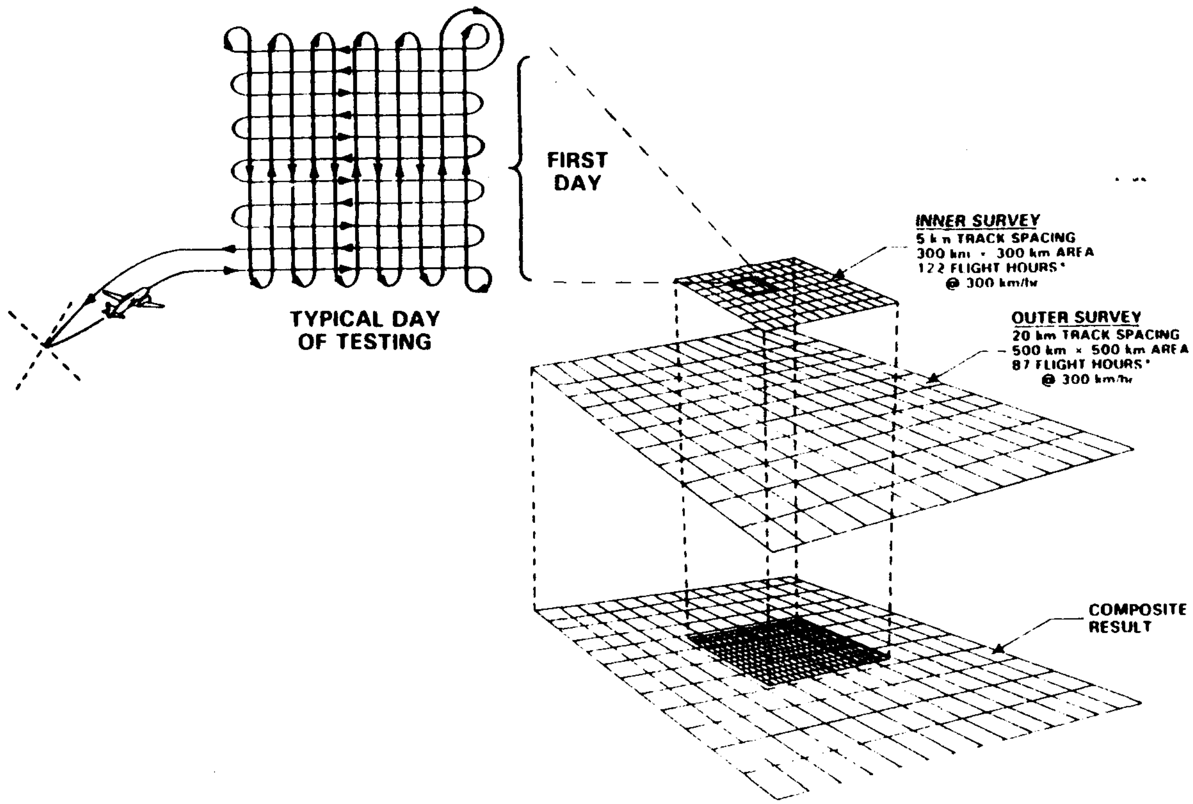
TWO ALTERNATIVE FLIGHT TEST PATTERNS — PLAN I



*TIME TO FLY GRID TRACKS ONLY

FINAL GRID PATTERN CONSISTS OF

- INNER 300 km × 300 km ZONE WITH UNIFORM 5 km GRID
- OUTER ZONE, 100 km THICK, WITH UNIFORM 20 km GRID
- EVERY FOURTH TRACK IS REPEATED WITHIN INNER ZONE
- TOTAL FLIGHT TIME REQUIRED — 209 hours

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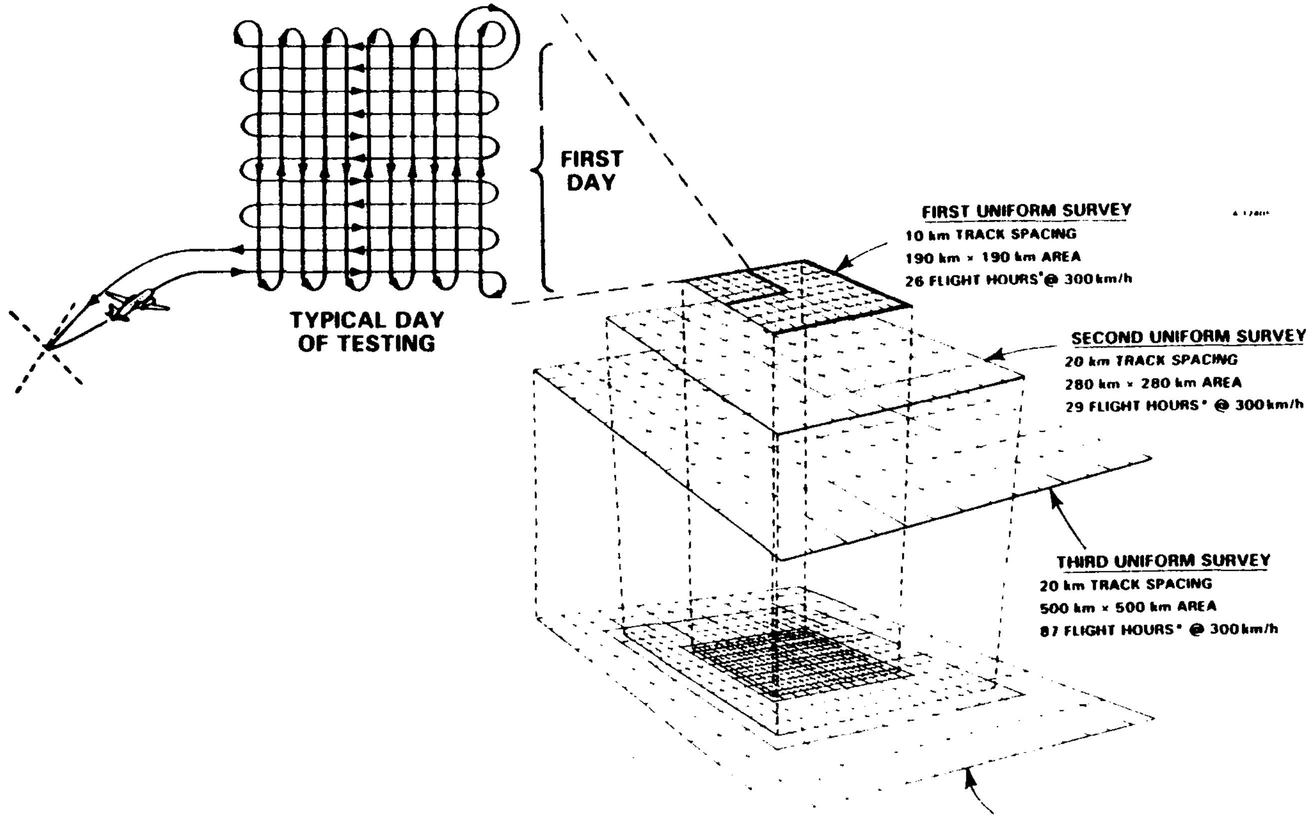
TWO ALTERNATIVE FLIGHT TEST PATTERNS — PLAN II



*TIME TO FLY GRID TRACKS ONLY

FINAL GRID PATTERN CONSISTS OF

- INNER 190 km × 190 km ZONE WITH UNIFORM 5 km GRID
- MIDDLE ZONE, 45 km THICK, WITH UNIFORM 10 km GRID
- OUTER ZONE, 110 km THICK, WITH UNIFORM 20 km GRID
- TOTAL FLIGHT TIME REQUIRED — 142 hours

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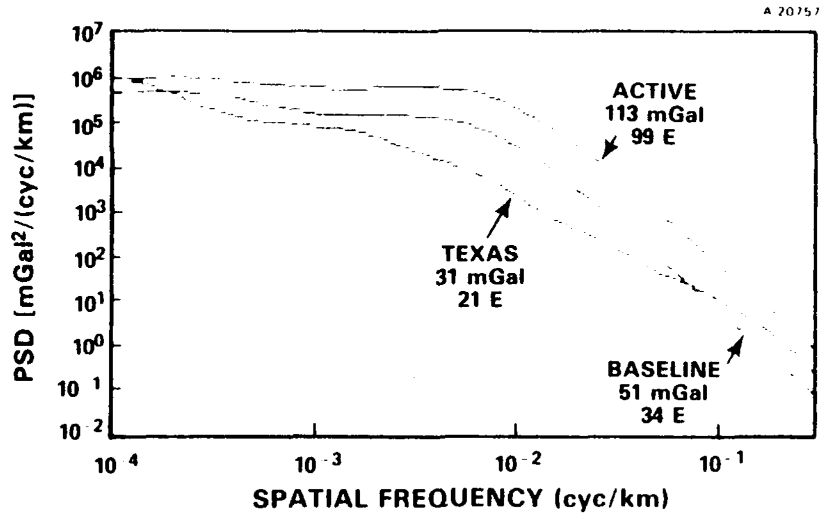
GRAVITY FIELD IN NORTH TEXAS TEST AREA

- ALONG-TRACK PSDs OF GRAVITY DATA PROVIDED BY DMAAC
- LONG WAVELENGTH FIELD CHARACTERIZED BY GEM10B (deg 0-36) AND RAPP (deg 37-180) DEGREE VARIANCE MODELS
- COMPOSITE "NORTH TEXAS" COVARIANCE MODEL FITTED USING ATTENUATED WHITE NOISE FUNCTIONAL FORM

COMPARISON WITH OTHER MODELS



- REALIZATION BY NSWC-DL OF SYNTHETIC DATA USING NORTH TEXAS MODEL WILL PROVIDE TOOL TO COMMUNITY FOR DEVELOPING, TESTING AND VALIDATING GGSS DATA PROCESSING SOFTWARE

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PROJECTED GGSS SURVEY PERFORMANCE USING DIFFERENT GRAVITY FIELD MODELS

	RMS SURVEY ERROR		ERROR AS A PERCENT OF RMS GGSS SPECIFICATION	
GRAVITY FIELD MODEL	DEFLECTION OF THE VERTICAL ($\widehat{sec}$)	VERTICAL GRAVITY DISTURBANCE (mgal)	DEFLECTION OF THE VERTICAL ($\widehat{sec}$)	VERTICAL GRAVITY DISTURBANCE (mgal)
ATTENUATED WHITE NOISE (AWN)	0.095	0.60	53%	67%
BASELINE	0.11	0.69	61%	77%
NORTH TEXAS	$\boxed{0.12}$	$\boxed{0.75}$	$\boxed{67\%}$	$\boxed{83\%}$
ACTIVE	0.14	0.91	78%	101%

- NOMINAL SURVEY CONDITIONS (5 km GRID, 600 m ALTITUDE, 300 kt AIRSPEED
- $55.0 + 1.7 \times 10^{-4}/f^{1.6}\ E^2/Hz \quad (17.5 + 1.06 \times 10^{-3}/\omega^{1.6}\ E^2 sec/rad)$
- WAVELENGTHS SHORTER THAN 500 km
- INCLUDES ALL KNOWN ERROR SOURCES AS WELL AS ALLOCATIONS OF 0.2 mgal AND 0.09 $\widehat{sec}$ FOR INACCURACY IN DATA REDUCTION ALGORITHMS

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SUMMARY PERSPECTIVE

GGSS PROGRAM OFFICE AND DMA HAVE ESTABLISHED AN ENVIRONMENT DESIGNED TO ANTICIPATE AND AVERT POTENTIAL DELAYS IN THE TEST PROGRAM

VARIABLES AFFECTING TEST DESIGN AND DATA REDUCTION ARE WELL UNDERSTOOD

OUTLOOK IS BRIGHT FOR SUCCESSFUL GGSS TESTING IN THE NEAR FUTURE

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A TEMPLATE APPROACH TO GGSS DATA REDUCTION

12 - 13 February 1985

Prepared for:
THIRTEENTH MOVING BASE GRAVITY GRADIOMETER REVIEW
United States Air Force Academy
Colorado

Prepared by:
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James V. White

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FOREWORD

This document contains material used in a presentation given by The Analytic Sciences Corporation. The material is not intended to be self-explanatory, but rather should be considered in the context of the overall presentation.

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OVERVIEW

- THE TEMPLATE METHOD—A PERSPECTIVE VIEW
- APPROPRIATE QUANTITY TO BE ESTIMATED DURING GGSS TESTING
- SIMULATION RESULTS
- CONCLUSIONS

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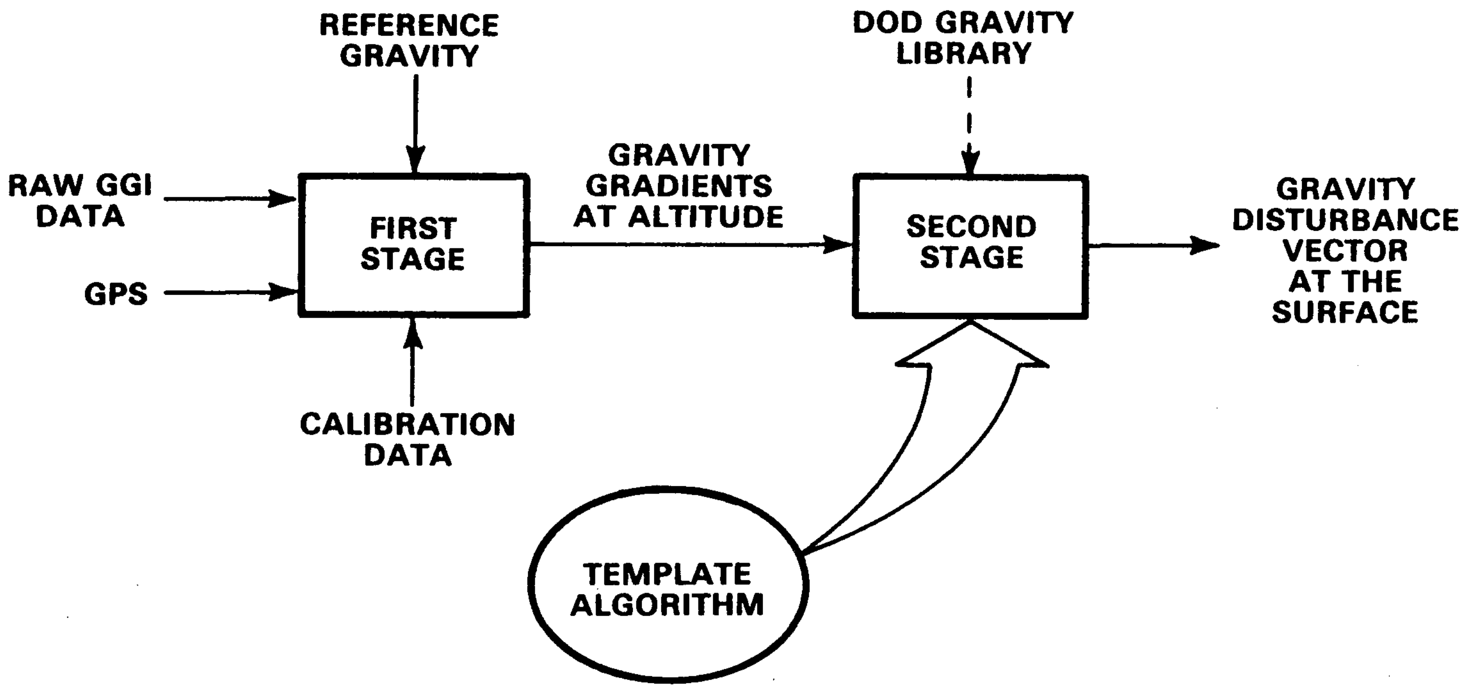
GGSS DATA PROCESSING



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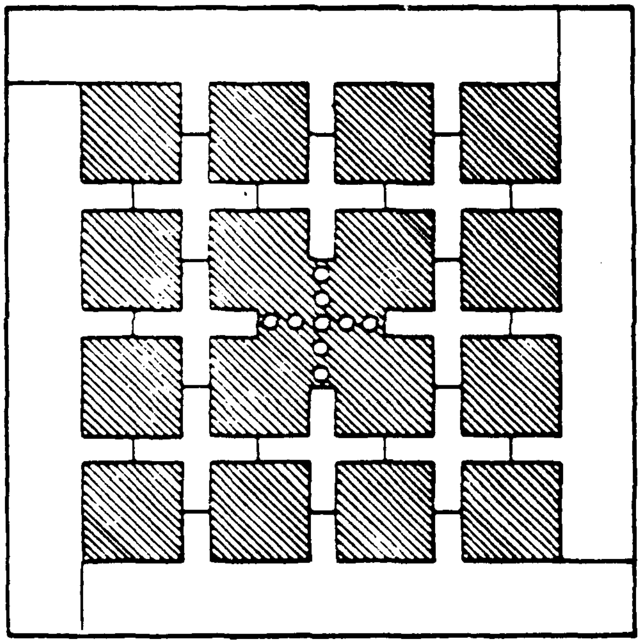

ESTIMATION OF THE GRAVITY DISTURBANCE VECTOR

TEMPLATE APPROACH

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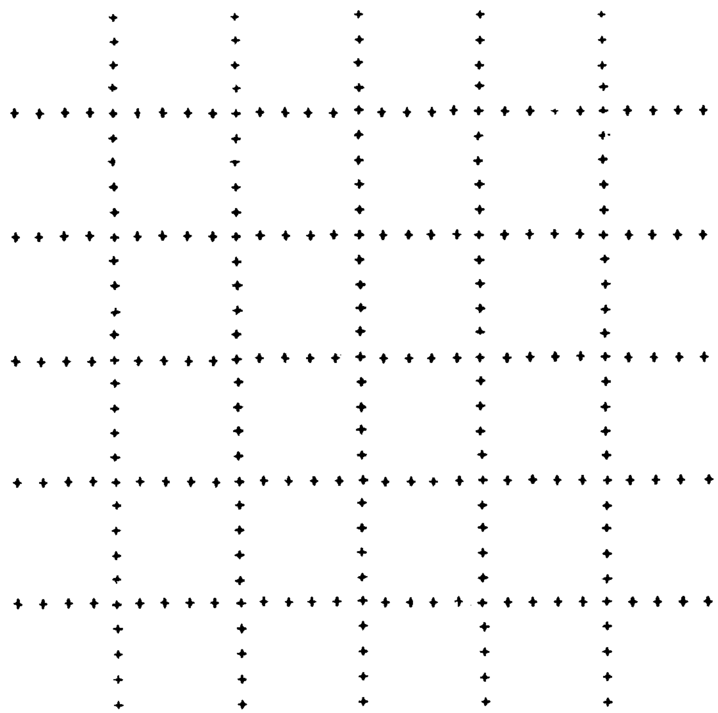

TWO STEPS:

1) AVERAGE GRADIENT MEASUREMENTS OVER TEMPLATE ZONES

2) USE OPTIMAL ESTIMATION TECHNIQUES TO DETERMINE THE GRAVITY DISTURBANCE VECTOR AT THE CENTER OF THE TEMPLATE FROM ZONE AVERAGES

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LEAST-SQUARES FORMULATION OF THE ESTIMATION PROBLEM

$$\underline{\hat{\delta}} = C_{\underline{\delta},\underline{\Gamma}} \left[C_{\underline{\Gamma},\underline{\Gamma}} + N \right]^{1} \underline{m}$$

GRAVITY
DISTURBANCE
VECTOR
ESTIMATES

CROSSCOVARIANCE
BETWEEN
GRAVITY
DISTURBANCE AND
TEMPLATE AVERAGES

AUTOCOVARIANCE
OF TEMPLATE
AVERAGES

AUTOCOVARIANCE
OF ERRORS IN
TEMPLATE
AVERAGES

TEMPLATE
AVERAGES

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CHARACTERISTICS OF THE TEMPLATE APPROACH

- REDUCES COMPUTATIONAL REQUIREMENTS WHILE MAINTAINING NEAR-OPTIMALITY
- PROVIDES A MEASURE OF THE ACCURACY OF THE ESTIMATES
- TEMPLATE AND STATISTICAL GRAVITY MODEL CAN BE CHOSEN TO ACCOUNT FOR THE CHARACTERISTICS OF THE LOCAL GRAVITY FIELD
- SET OF TEMPLATES AND THEIR ESTIMATION GAINS CAN BE PRECOMPUTED
- TEMPLATE CAN BE ADJUSTED TO NON-UNIFORM SURVEY PATTERNS

A 20792

DICHOTOMY BETWEEN GGSS TESTING AND OPERATIONAL DATA PROCESSING

GGSS TESTING		OPERATIONAL DATA PROCESSING
• DOD GRAVITY LIBRARY • LIMITED SURVEY DATA	DATA	• DOD GRAVITY LIBRARY • LARGE DATA SETS
• VERIFY ACCURACY OF GRADIOMETER	PURPOSE	• OBTAIN BEST ESTIMATE OF GRAVITY
• COMPARE SEPARATE ESTIMATES	METHODOLOGY	• BLEND AVAILABLE DATA

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APPROPRIATE QUANTITY TO BE ESTIMATED DURING GGSS TESTING

THE VECTOR QUANTITY TO BE ESTIMATED SHOULD BE SUCH THAT

- IT MATCHES THE POINT DISTURBANCE AT HIGH FREQUENCIES
- IT IS ESSENTIALLY FREE OF LOW-FREQUENCY GRAVITY
- IT CAN BE ACCURATELY COMPUTED FROM INDEPENDENT DATA

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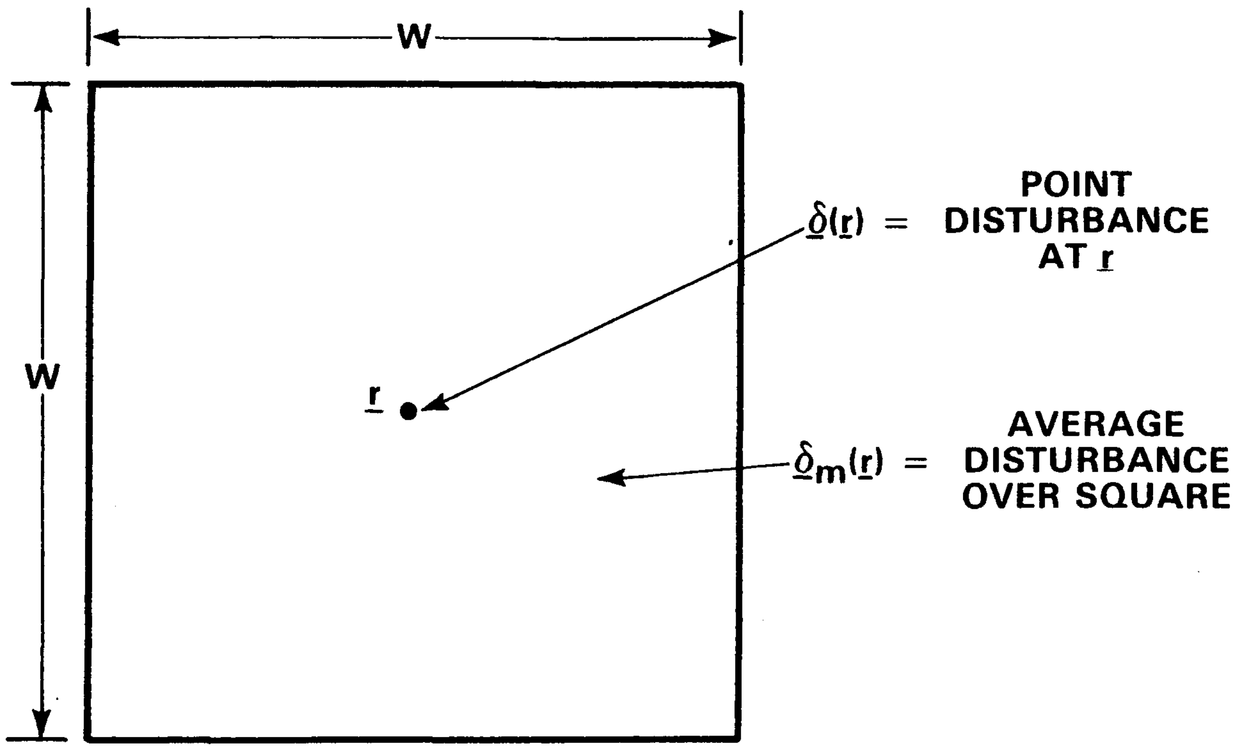
DEFINITION OF RESIDUAL GRAVITY DISTURBANCE VECTOR



THE RESIDUAL GRAVITY DISTURBANCE VECTOR IS THE DEPARTURE OF THE POINT DISTURBANCE FROM ITS LOCAL MEAN

$$\underline{d}\,(\underline{r}) \triangleq \underline{\delta}\,(\underline{r}) - \underline{\delta}_m\,(\underline{r})$$

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RESIDUAL DISTURBANCE SPECTRUM

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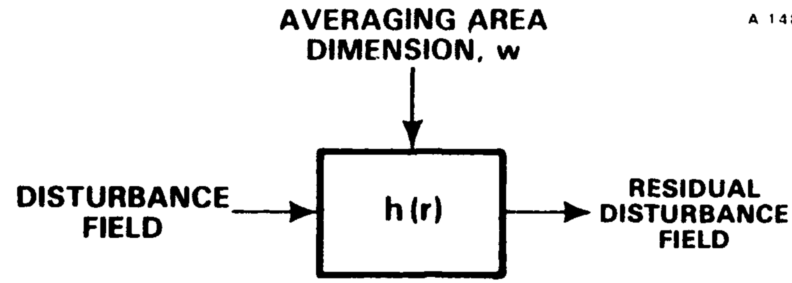
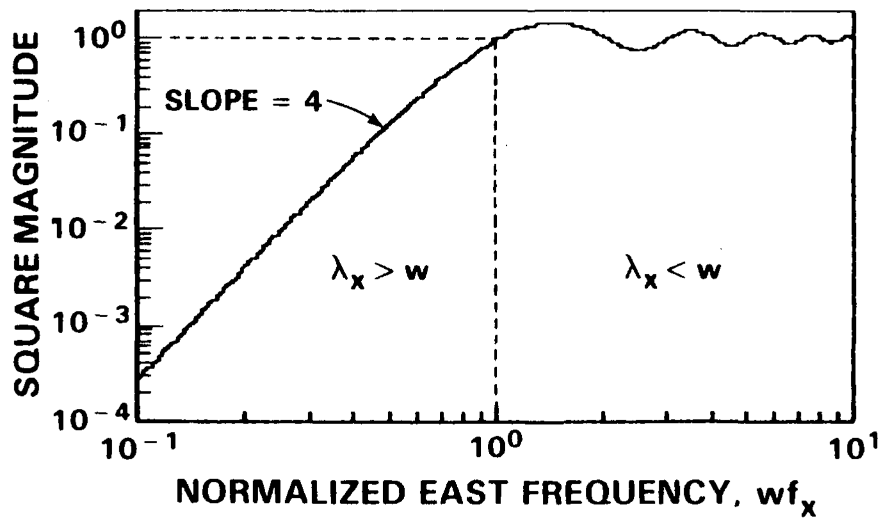


$$|H(f_x, f_y)|^2 = [1 - \mathrm{sinc}(wf_x)]^2 [1 - \mathrm{sinc}(wf_y)]^2$$

FREQUENCY RESPONSE



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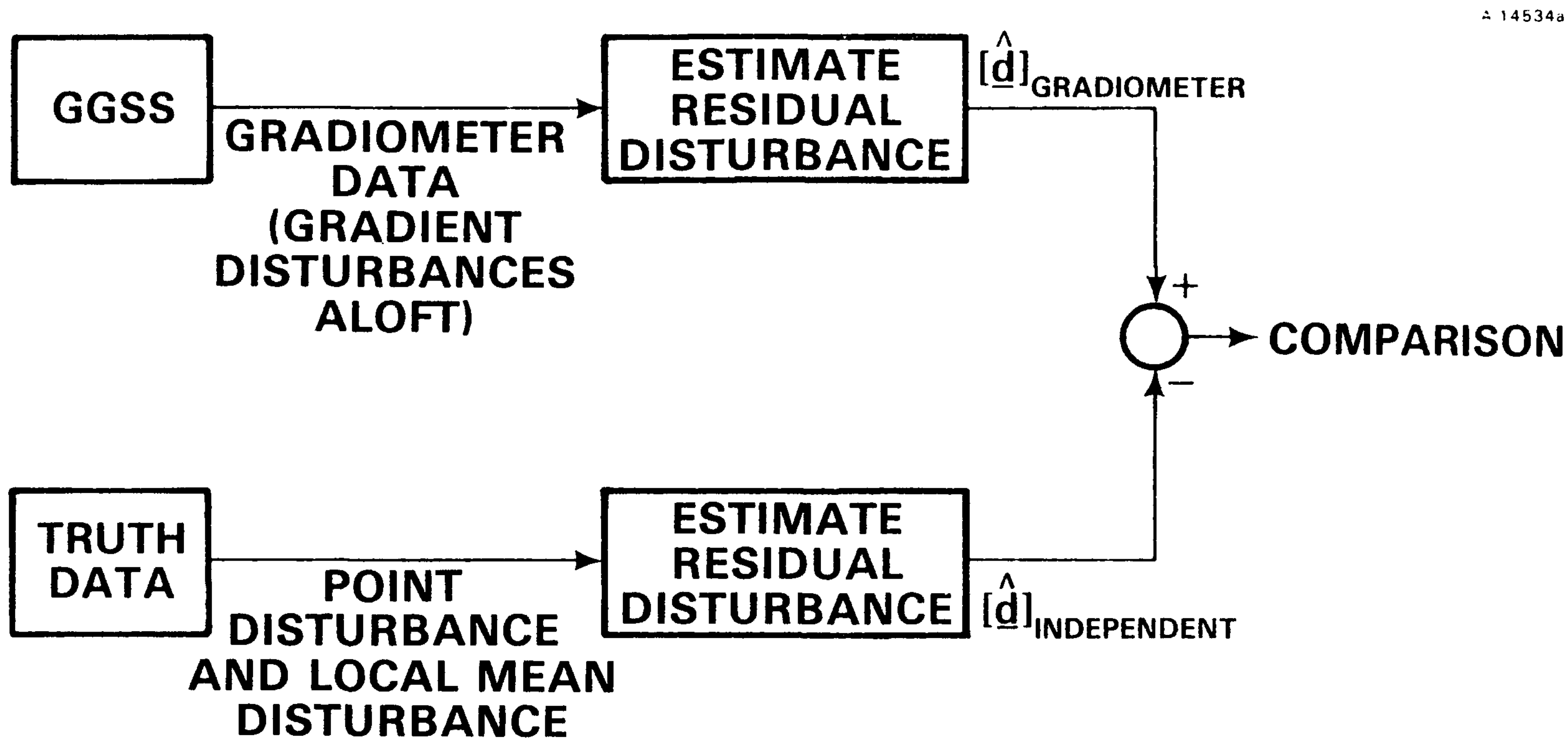
GGSS TESTING COMPARISON



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SURVEY SIMULATION

PURPOSE

- TO VERIFY END-TO-END CONSISTENCY OF ESTIMATION ALGORITHM
- TO GAIN FAMILIARITY WITH DATA HANDLING ISSUES

GEOMETRY

- 100-km × 100-km SURVEY AREA IS SUFFICIENT

DATA

- GRADIOMETER DATA — VERTICAL-VERTICAL GRADIENT ALOFT
- TRUTH DATA — VERTICAL DISTURBANCE AT SURFACE

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SIMULATED DATA GEOMETRY

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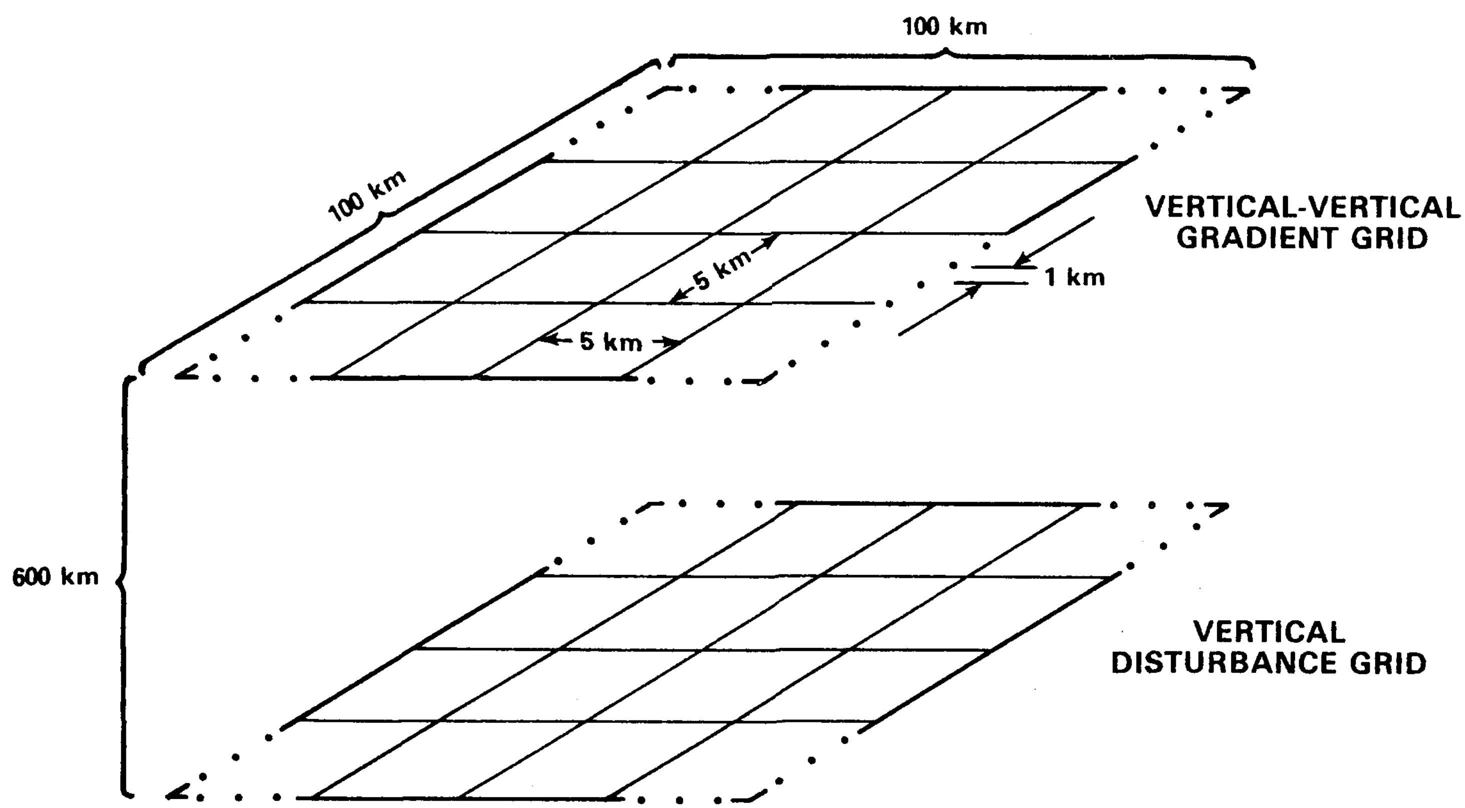

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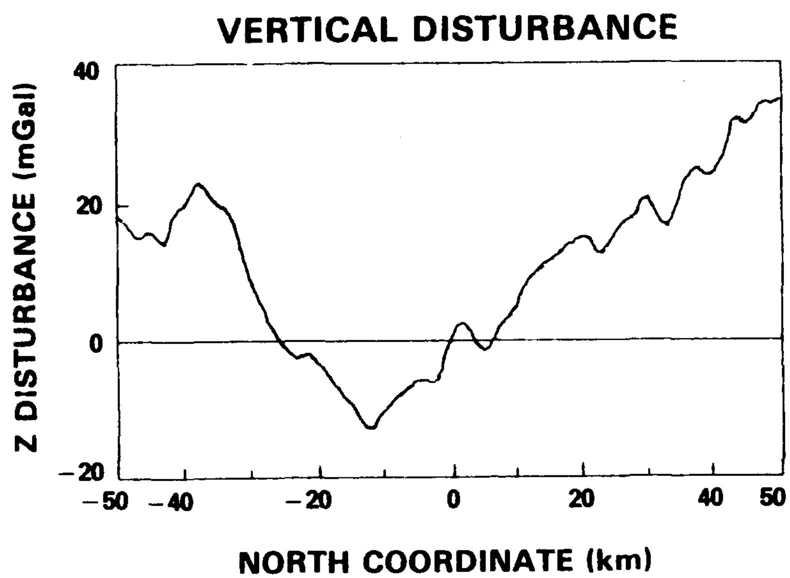
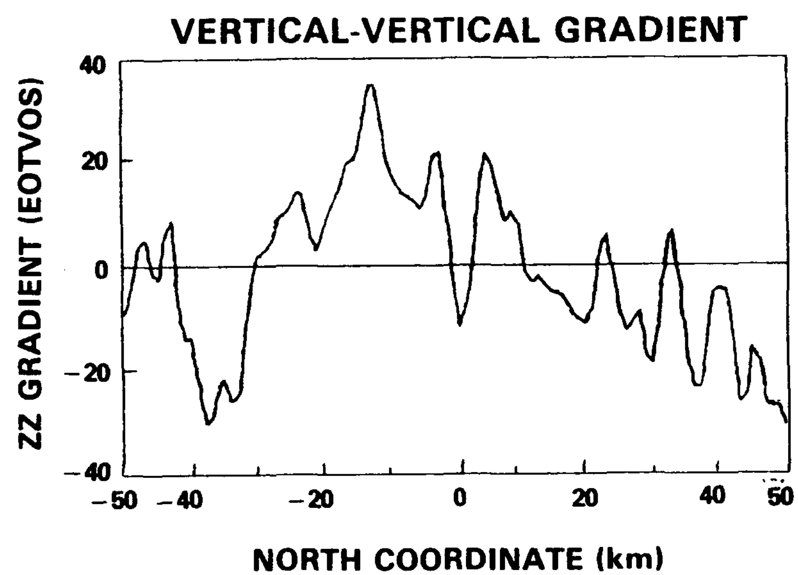
SAMPLE SIMULATED DATA





STATISTICS OF SIMULATED DATA

	VERTICAL DISTURBANCE (mGal)	VERTICAL-VERTICAL GRADIENT (EÖTVOS)
MEAN VALUE	9.35	2.91
RMS VALUE	16.88	13.57

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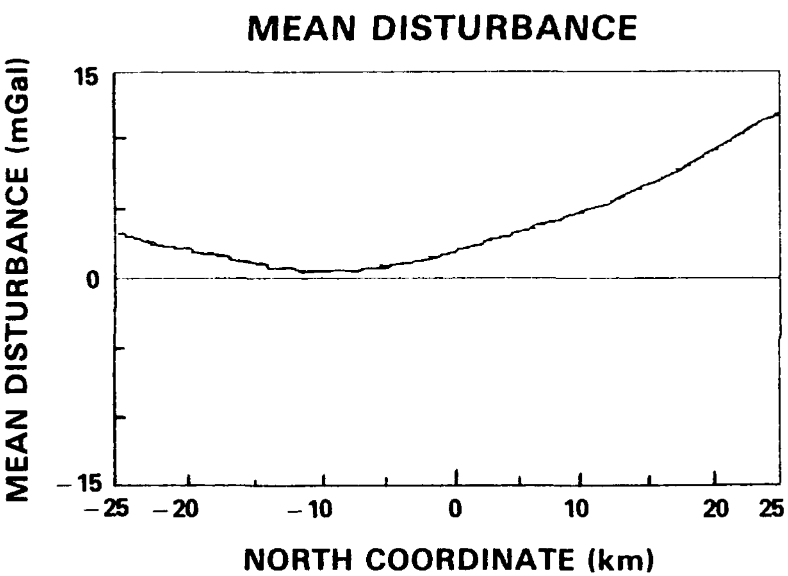
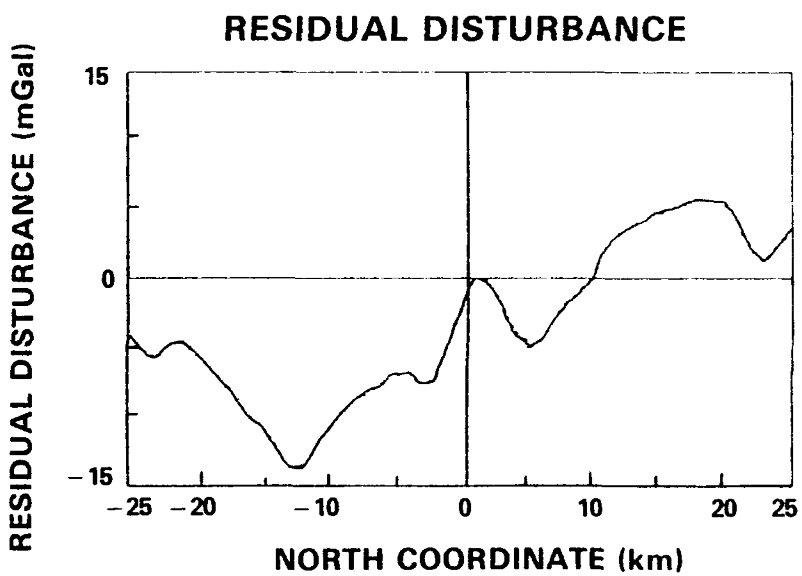
DECOMPOSITION OF THE VERTICAL DISTURBANCE INTO MEAN AND RESIDUAL DISTURBANCE





- MEAN DISTURBANCE COMPUTED OVER A SQUARE WITH SIDES W = 50 km
- MEAN DISTURBANCE + RESIDUAL DISTURBANCE = TOTAL DISTURBANCE
- PURPOSE IS TO ESTIMATE RESIDUAL DISTURBANCE

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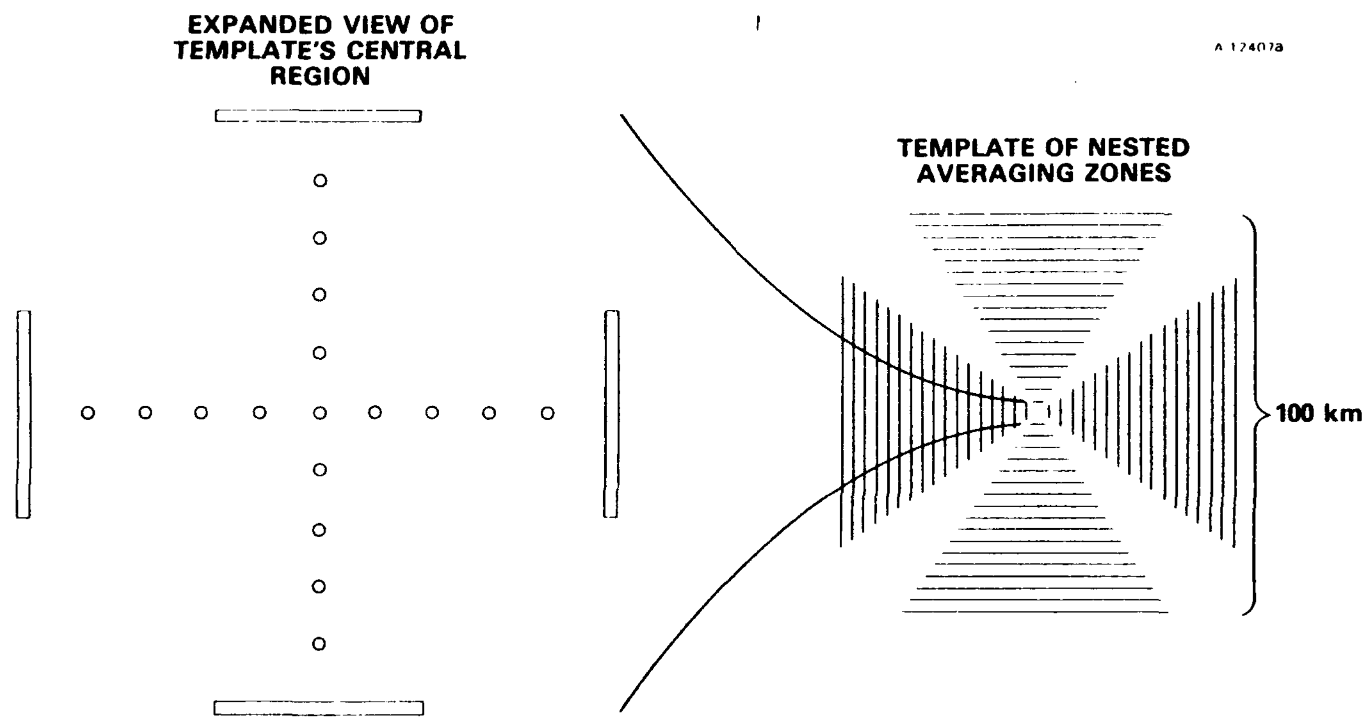
TEMPLATE METHOD ESTIMATION RESULTS (UNOPTIMIZED TEMPLATE GEOMETRY)



- TEMPLATE GEOMETRY RESULTING FROM TASC'S INITIAL OPTIMIZATION STUDIES
- ACTUAL RESIDUAL DISTURBANCE VALUE = −1.96 mGal

  ESTIMATED VALUE = −1.88 mGal

  PREDICTED RMS ERROR = 0.64 mGal

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CONCLUSIONS

- END-TO-END CHECK ON CONSISTENCY OF FORMULATION HAS BEEN COMPLETED
- SIMULATION RESULTS AGREE WITH PREDICTED THEORETICAL ACCURACY
- OPTIMIZATION OF TEMPLATE FOR GGSS TESTING IS CONTINUING

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SYNTHETIC DATA FOR GGSS STAGE II EVALUATION

By

PETER UGINCIUS

NSWC

FEB 1985

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SYNTHETIC DATA FOR GGSS STAGE II EVALUATION

1. STOCHASTIC MODEL
   - STATISTICS KNOWN EXACTLY (AWN)
   - VERTICAL DIPOLES
   - FITTED TO TEST AREA, GEM10B, RAPP180

2. QUASI-DETERMINISTIC MODEL
   - DETERMINISTIC LONG-WAVELENGTH FEATURE
   - STOCHASTIC SHORT-WAVELENGTH POWER
   - POINT MASSES AND/OR DIPOLES
   - REALISTIC: NON-STATIONARY, ANISOTROPIC

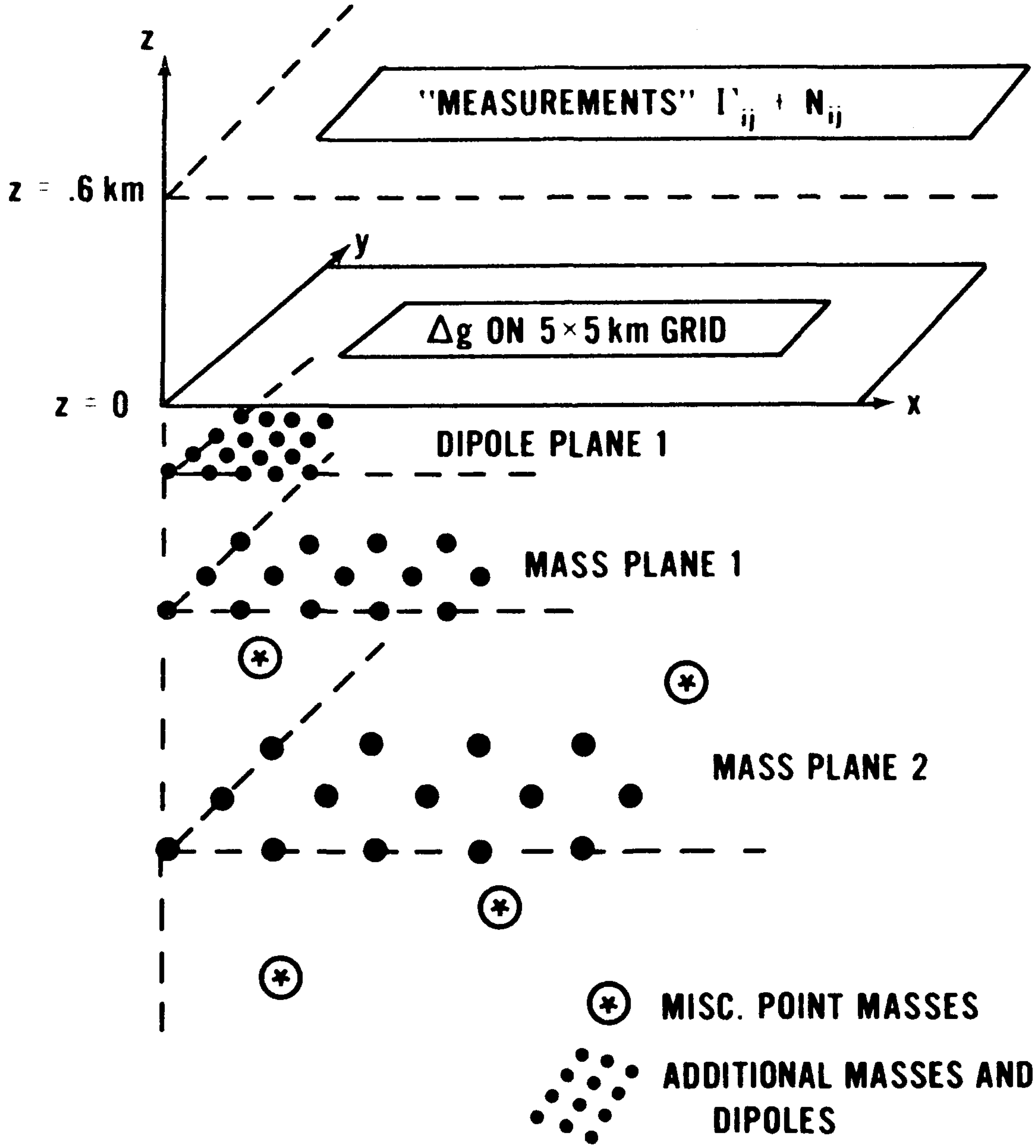
STOCHASTIC MODEL (AWN) PARAMETERS

LAYER NO.	DEPTH (km)	SPACING (km)	NO. OF * DIPOLES	σ_{DIPOLE} mgal·km^3
1	2.1	.84	384,400	3.2
2	5	2.0	73,984	87.4
3	16	6.4	9,604	5858
4	52	20.8	1,936	$4.98 \cdot 10^5$
5	161	64.4	729	$1.89 \cdot 10^7$
6	861	344.4	441	$1.65 \cdot 10^9$
7	2150	860.0	400	$4.85 \cdot 10^{10}$

TOTAL NO. OF DIPOLES: 471,494

* FOR 500 × 500 km SURVEY AREA

QUASI-DETERMINISTIC MODEL



GMNT PARAMETERS

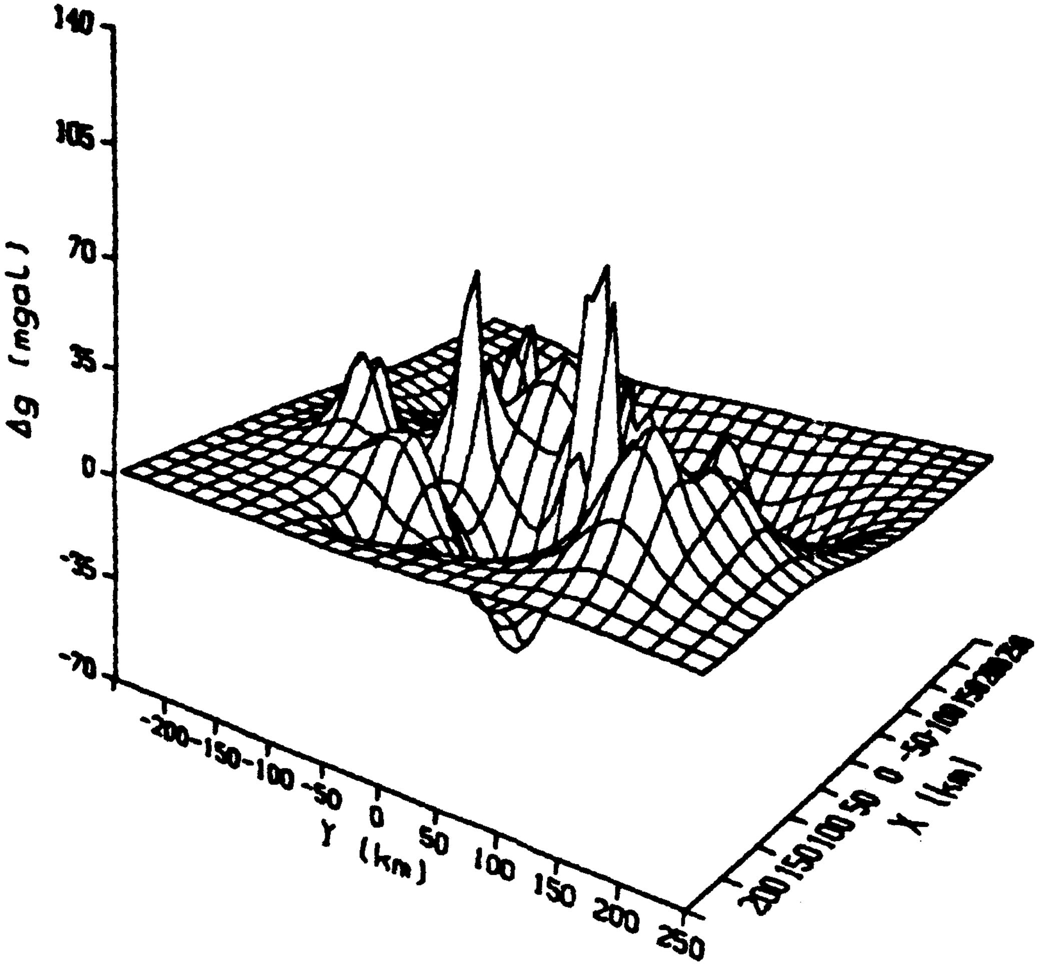
	MISC.	PLANE PARAM'S			TOTAL NO.		
	P. M.	$-z$	DEL*	$\sigma_{M,D}$	MASSES	DIPOLES	$\sigma_{\Delta g}$ (mgal)
GMNTA	25				25		17.5
GMNTB	36				36		19.2
GMNTC	36	105	70	10^5 (M)	205		20.9
GMNTE	36	30	20	3000 (M)	1726		23.4
GMNTF	36	25	10	$5 \cdot 10^4$ (D)	1726	3721	28.8

*UNITS: z(km), DEL(km), σ_M (mgal · km^2), σ_D (mgal · km^3)

RESULTS

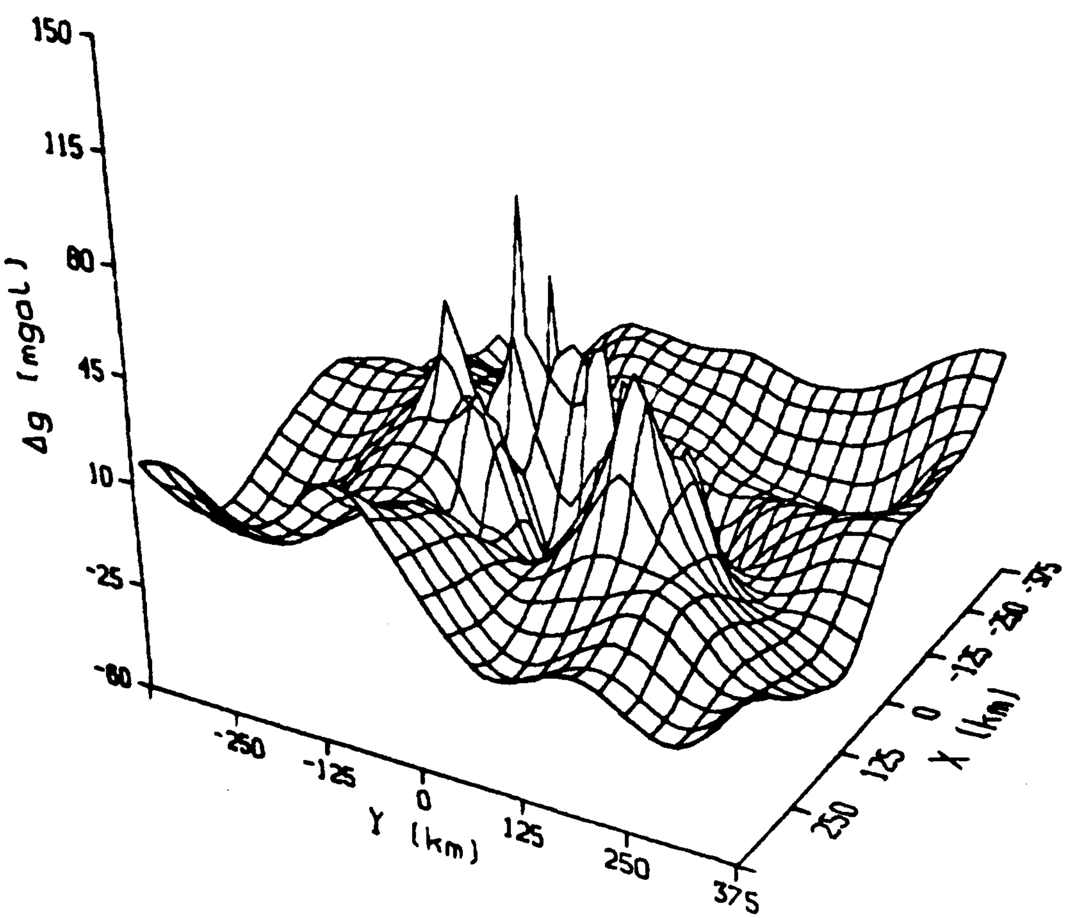
- 3-D Δg PROFILES
- Δg CONTOURS
- Δg vs X
- SINGLE TRACK PSD OF Δg
- AVERAGED PSD

GMNTA



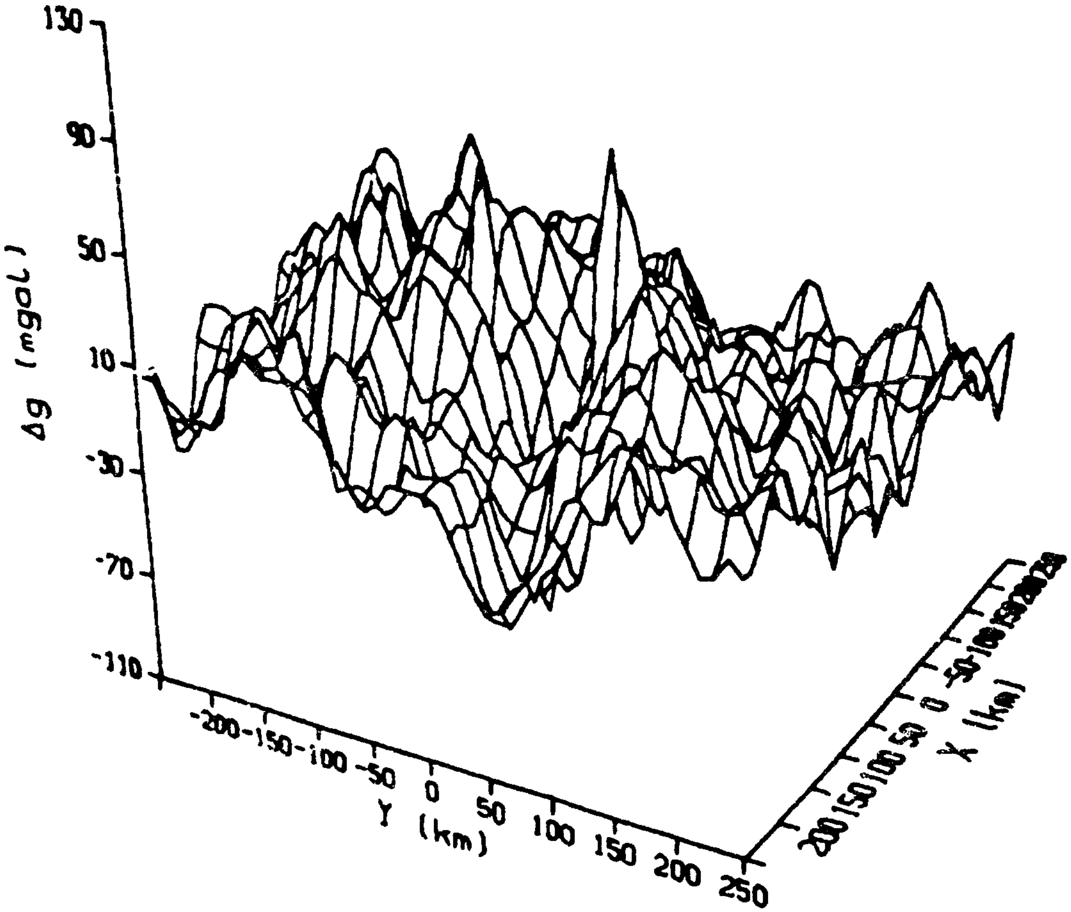
140
105
70
35
0
-35
-70
Δg (mgaL)
-200 -150 -100 -50 0 50 100 150 200 250
Y (km)
200 150 100 50 0 -50
X (km)

GMNTC



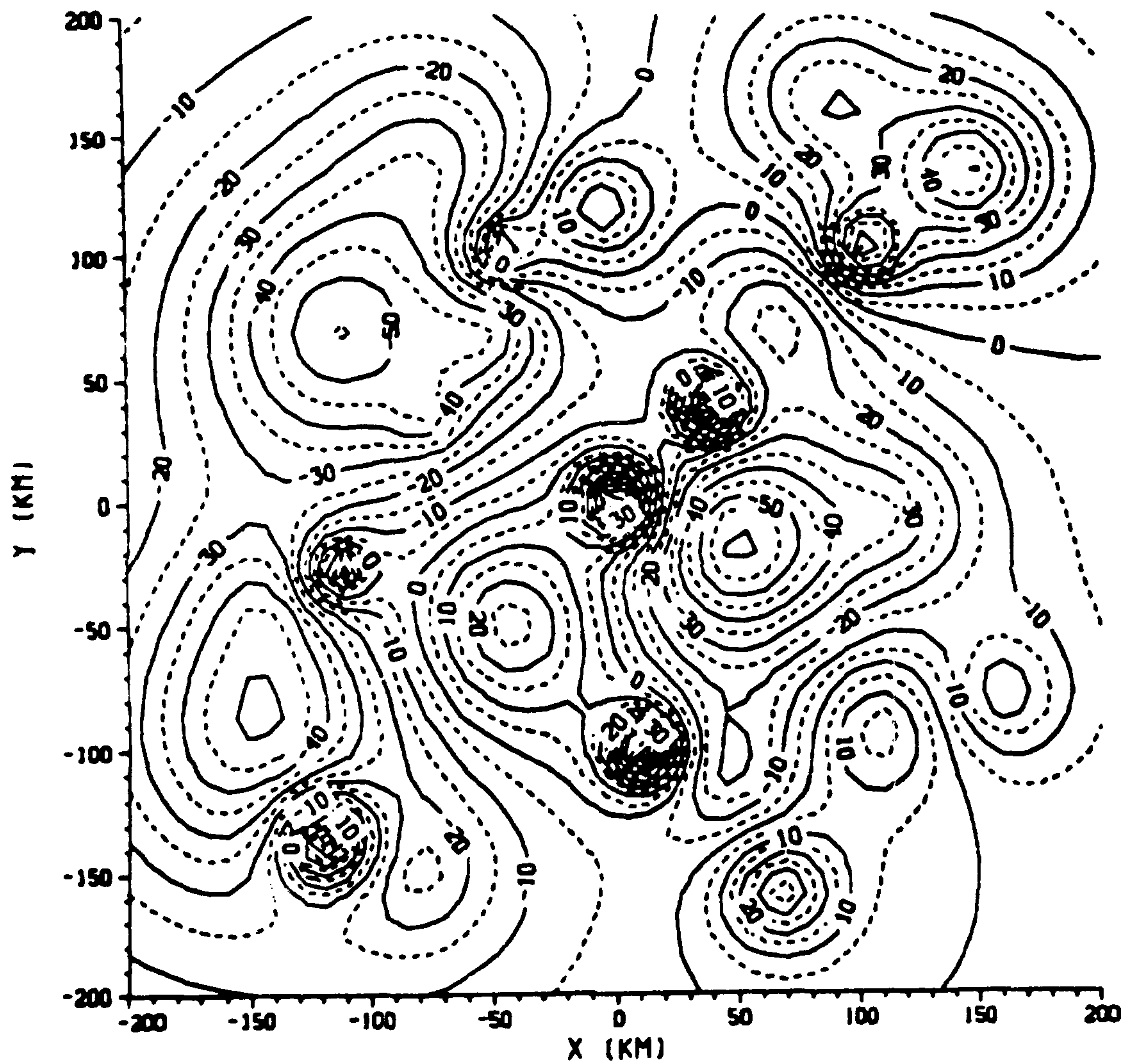
150
115
80
45
10
-25
-60
Δg (mgal)
-250
-125
0
125
250
375
Y (km)
250
125
0
-125
-250
-375
X (km)

GMNTF

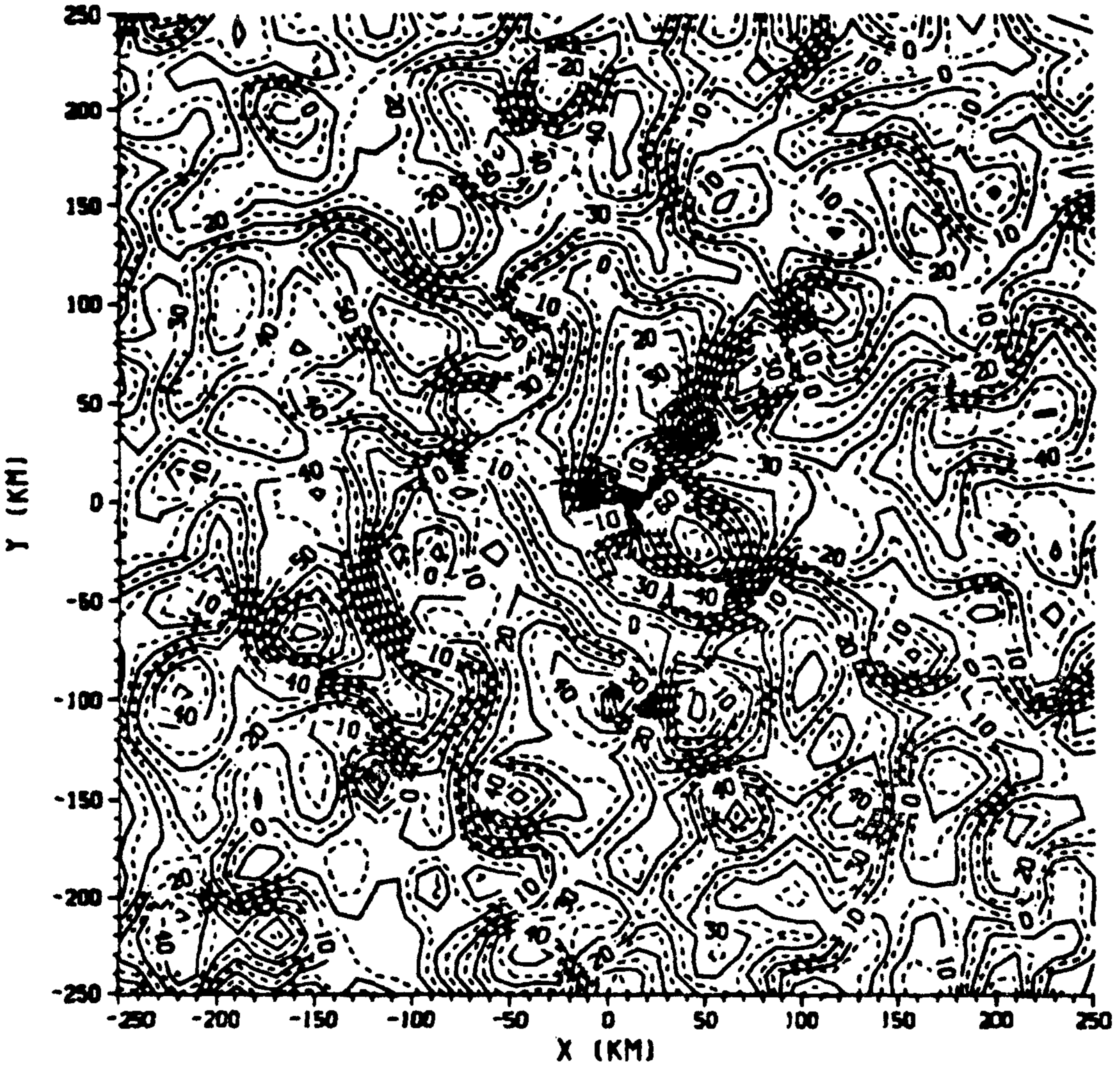


130
90
50
10
-30
-70
-110
Δg (mgal)
-200 -150 -100 -50 0 50 100 150 200 250
Y (km)
200 150 100 50 0 -50 -100
X (km)

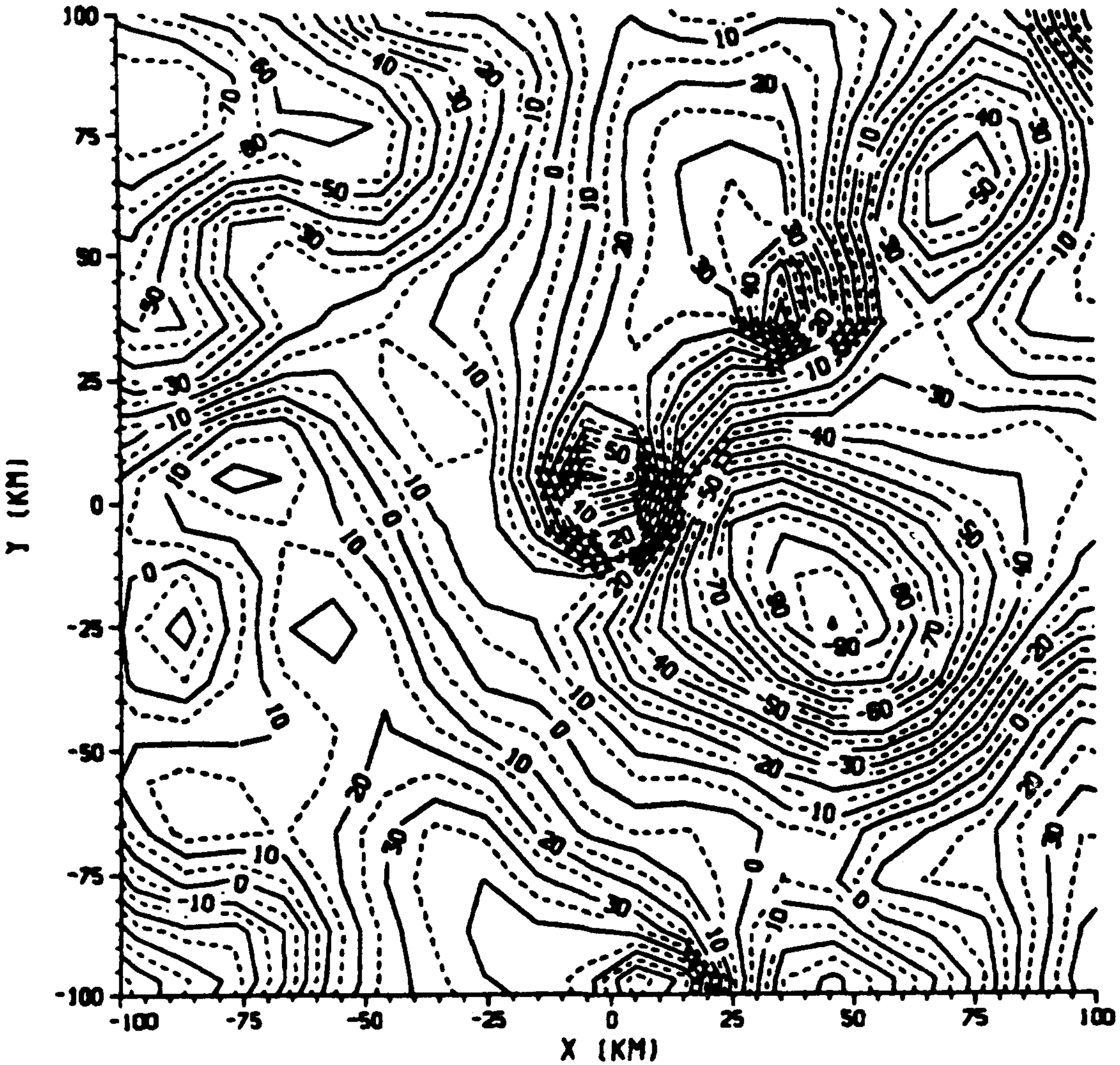
GMNTA



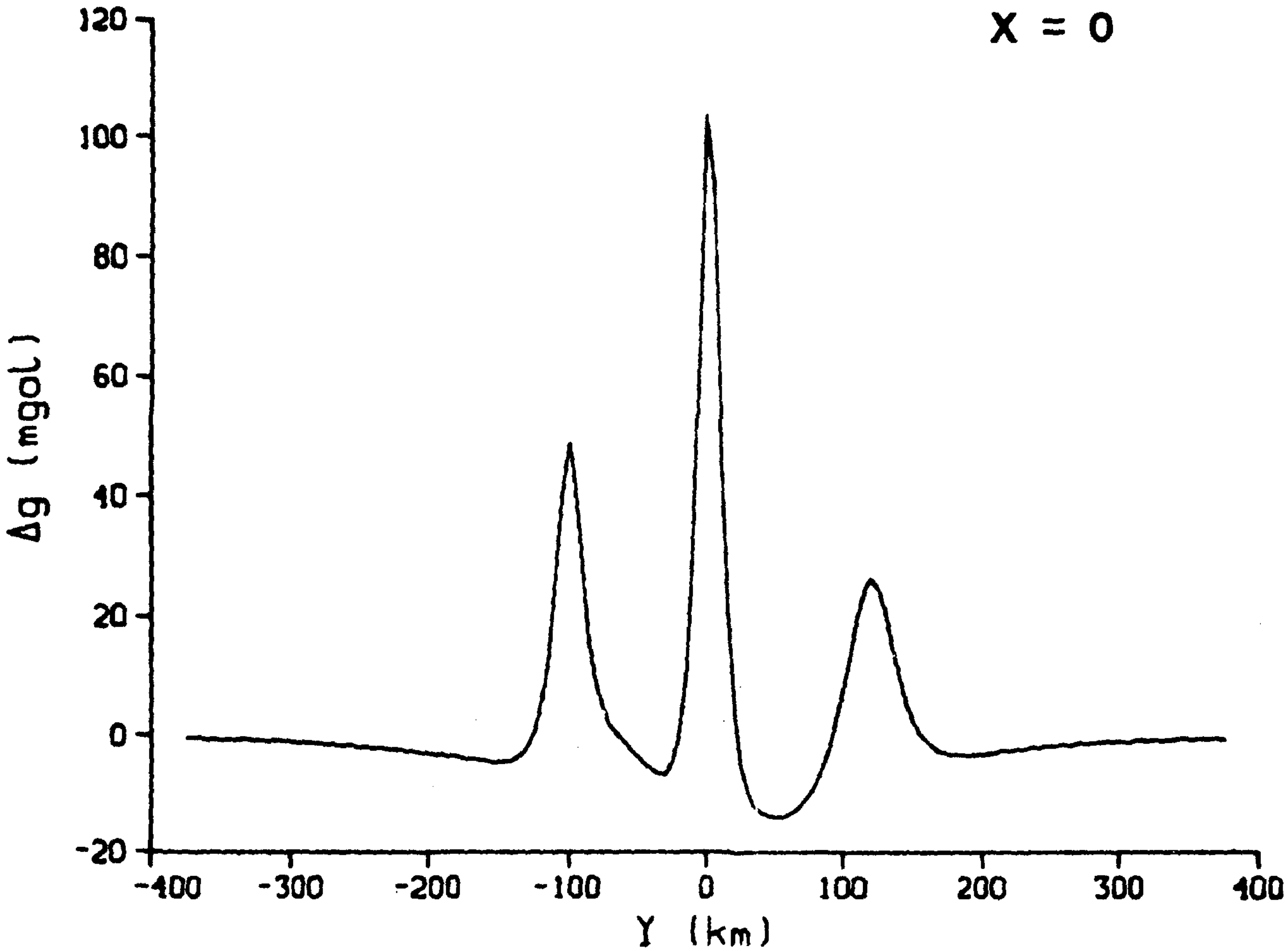
GMNTF



GMNTF

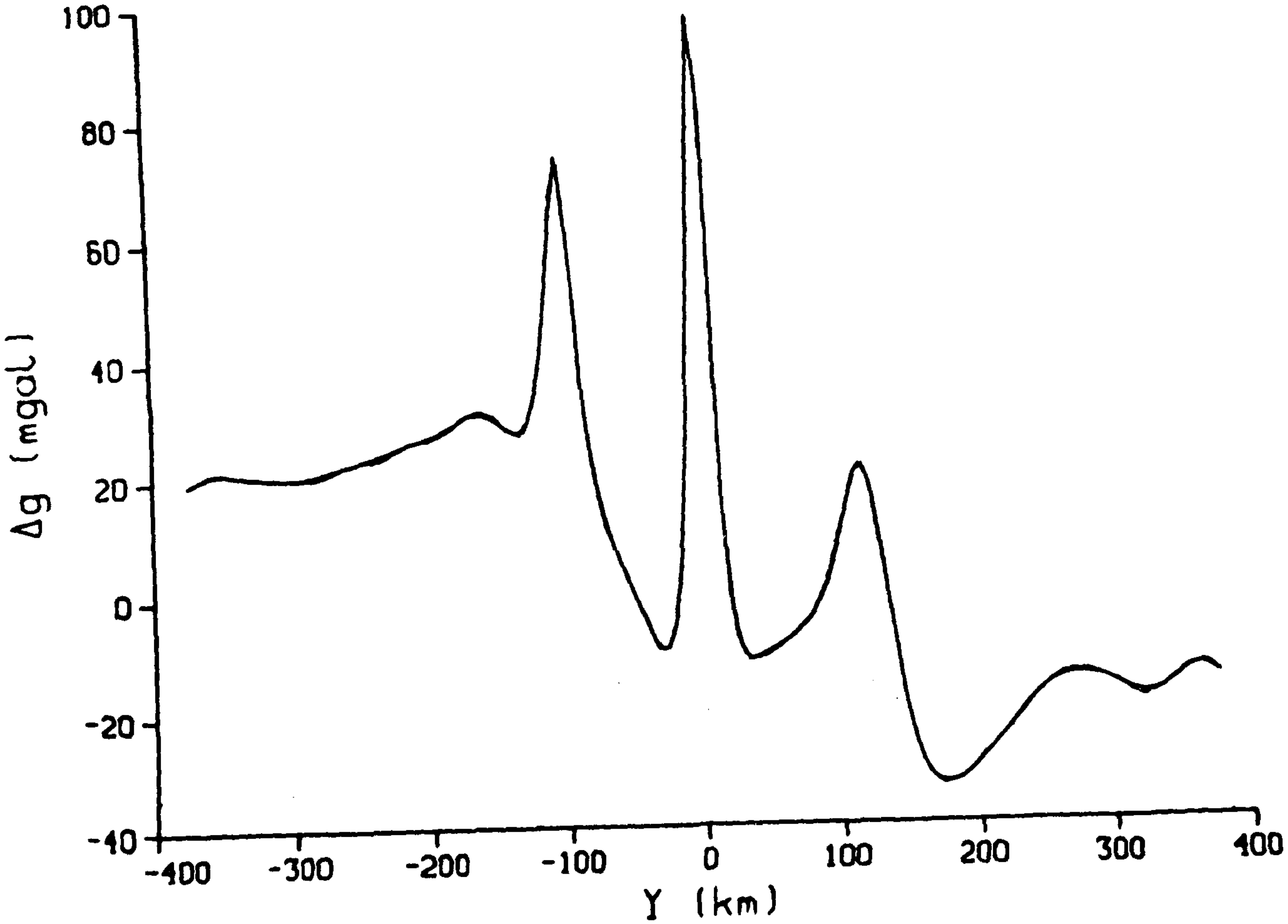


GMNTA


X = 0
120
100
80
60
40
20
0
-20
Δg (mgal)
-400
-300
-200
-100
0
100
200
300
400
Y (km)

GMNTE

X = 0



100
80
60
40
20
0
-20
-40
Δg (mgal)
-400
-300
-200
-100
0
100
200
300
400
Y (km)

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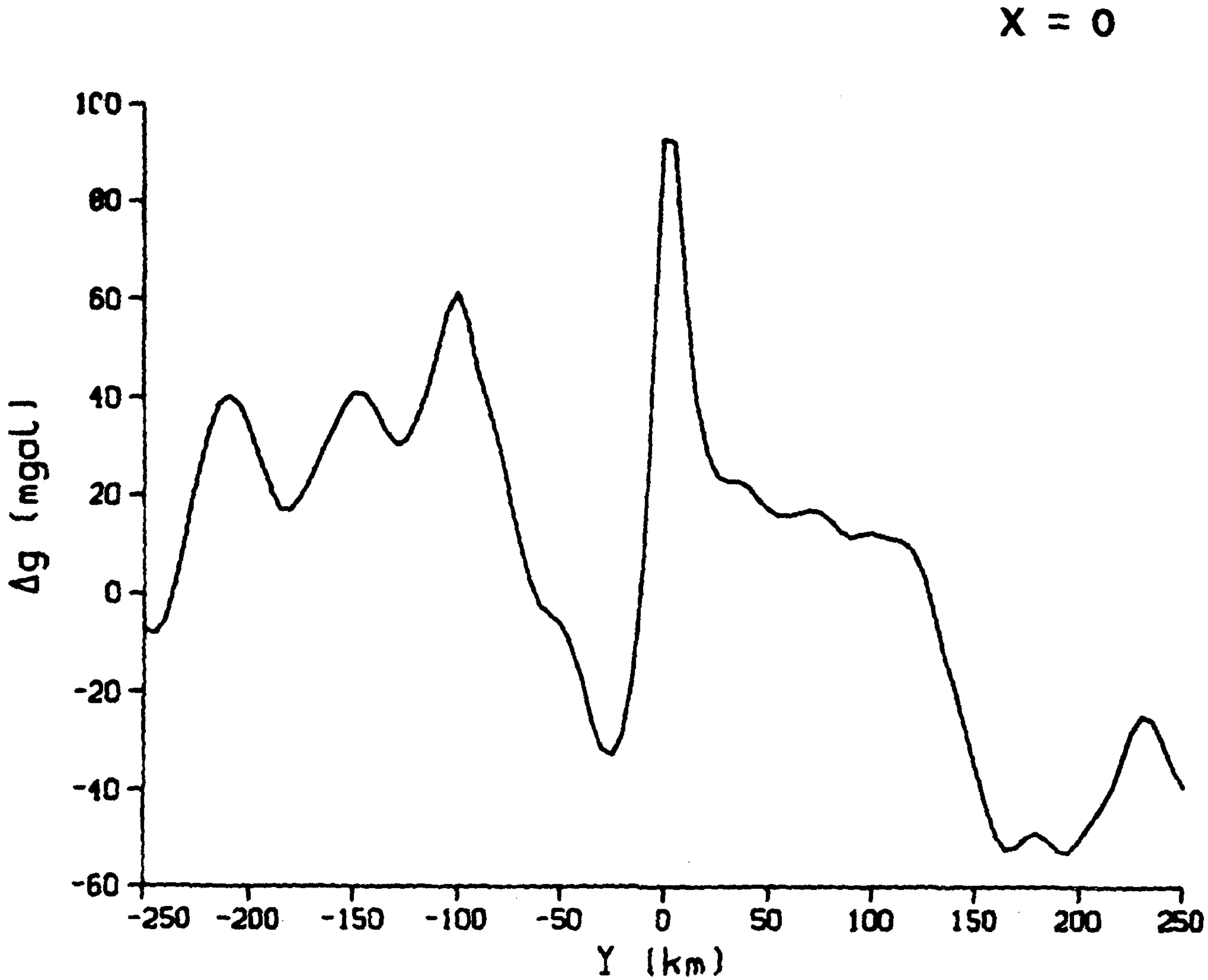
GMNTF


X = 0
100
80
60
40
20
0
-20
-40
-60
Δg (mgal)
-250 -200 -150 -100 -50 0 50 100 150 200 250
Y (km)

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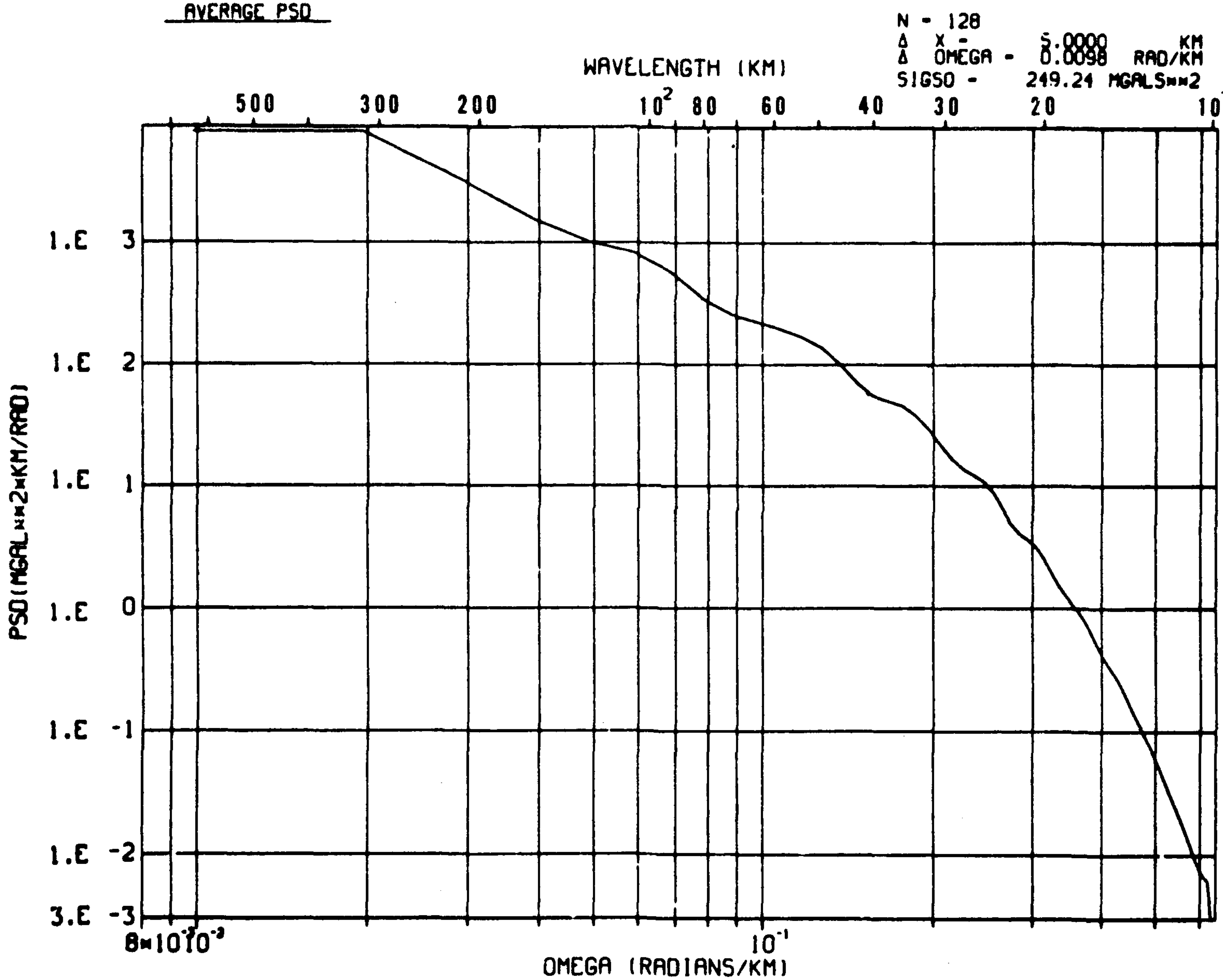
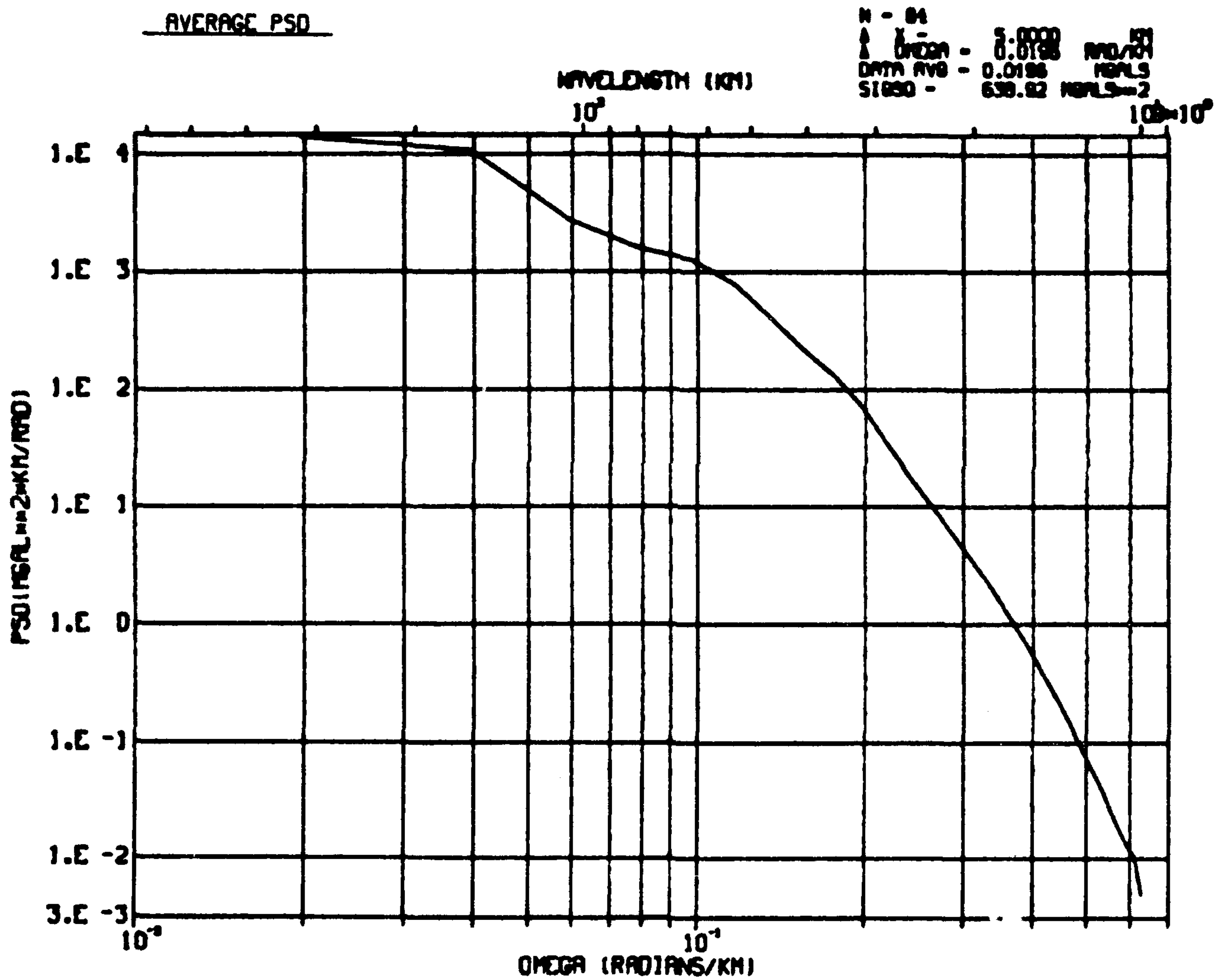
POWER SPECTRAL DENSITIES

AVERAGE PSD



GMNTA AVG PSD

POWER SPECTRAL DENSITIES



GMNTF

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Geospace Systems
CORPORATION

SP-101-2

POST-MISSION ADJUSTMENT OF
BELL GRAVITY GRADIOMETER DATA

12 February 1985

Presented at:

13th Annual Moving-Base Gravity
Gradiometer Review
USAF Academy, CO 80840

Wellesley Office Park
40 William Street
Wellesley, MA 02181
(617) 431-7666

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POST-MISSION ADJUSTMENT OF BELL GRAVITY GRADIOMETER DATA

JULIAN L. CENTER, JR.

G. SCOTT PEACOCK

STANLEY K. JORDAN

SPONSORED BY

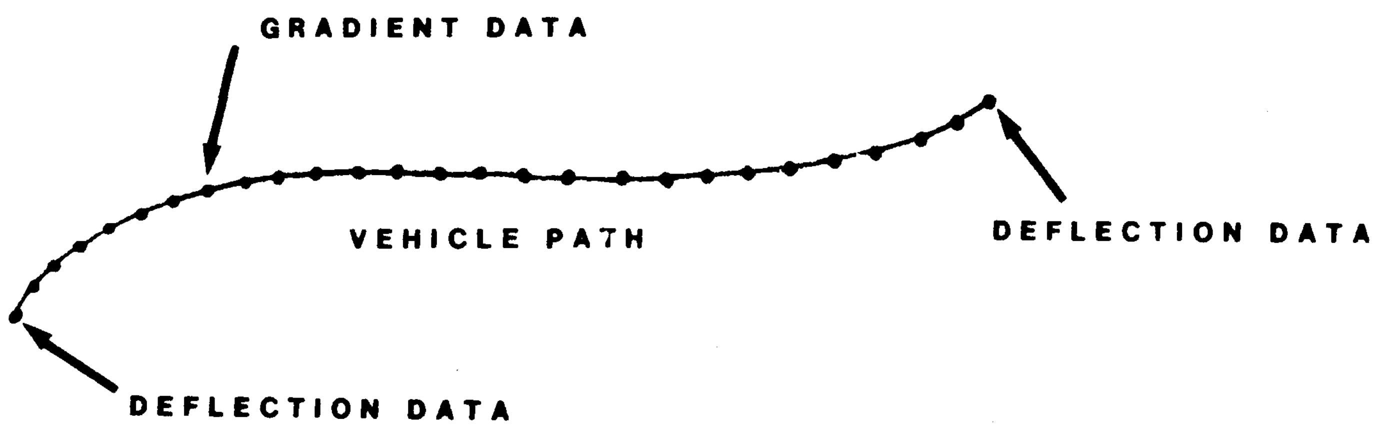
CENTER FOR GEODESY

U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES

FORT BELVOIR, VIRGINIA

Geospace Systems CORPORATION

STATEMENT OF THE PROBLEM



Geospace Systems CORPORATION

APPROACH

PARAMETRIC MODEL

AND

SEQUENTIAL SINGULAR VALUE DECOMPOSITION

SINGULAR VALUE DECOMPOSITION

(DATA) $\underline{z} = H\underline{x} + \underline{v}$

(SVD) $H = USV^T$

(ESTIMATE) $\underline{x} = VS^{-1}U^T\underline{z}$

DIAGONAL MATRIX

Geospace Systems CORPORATION

SINGULAR VALUE DECOMPOSITION

(DATA) $\underline{z} = H\underline{x} + \underline{v}$

(SVD) $H = USV^T$

(ESTIMATE) $\underline{x} = VS^{-1}U^T\underline{z}$

DIAGONAL MATRIX

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ADVANTAGES OF SVD

VERY STABLE

INTERPRETATION OF DATA IN STATE-SPACE

SEQUENTIAL

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SEQUENTIAL SVD

PROCESS SMALL BATCHES OF DATA

ELIMINATE WELL-ESTIMATED STATES

ELIMINATE REDUNDANT INFORMATION IN DATA

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SSVD VERSUS COLLOCATION

(EXAMPLE)

COLLOCATION

INVERT MATRIX 1000 × 1000

SSVD

LARGEST ARRAY 200 × 100

Geospace Systems CORPORATION

OTHER APPLICATIONS

AIRBORNE GGSS DATA PROCESSING

REAL-TIME (TRIDENT) DATA PROCESSING

Geospace Systems CORPORATION

MOVING BASE GRAVITY GRADIOMETER REVIEW

Book 2

Post Mission Data Reduction For Airborne Gradiometer Systems

Air Force Academy

Report No. 6501-927078 • FEBRUARY 12-13, 1985

Bell Aerospace TEXTRON
Division of Textron Inc

POST OFFICE BOX ONE • BUFFALO, NEW YORK 14240

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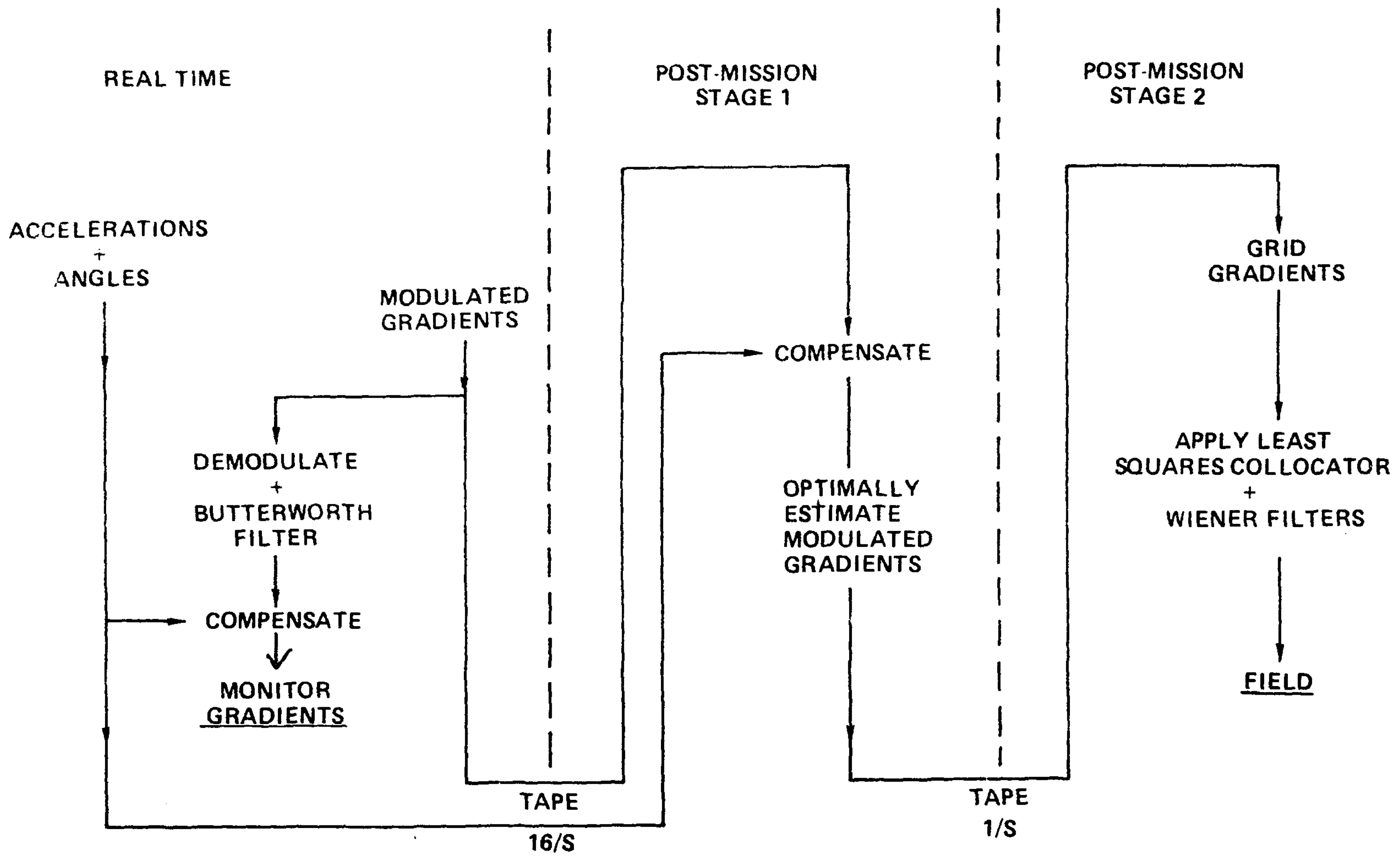
Part 1 - Optimal Extraction of Wide Bandwidth Gravity Gradients

The measurement of gravity gradients using the Bell Gradiometer in a moving ground vehicle or low altitude aircraft necessitates extraction of a wide bandwidth gravity signature in the presence of instrument and environmental noise. An optimal technique for accomplishing this is described. This technique incorporates a priori knowledge of those processes which generate the signature and noise but is adaptive to particular mission and instrument characteristics.

GGSS SIGNAL PROCESSING - OUTLINE



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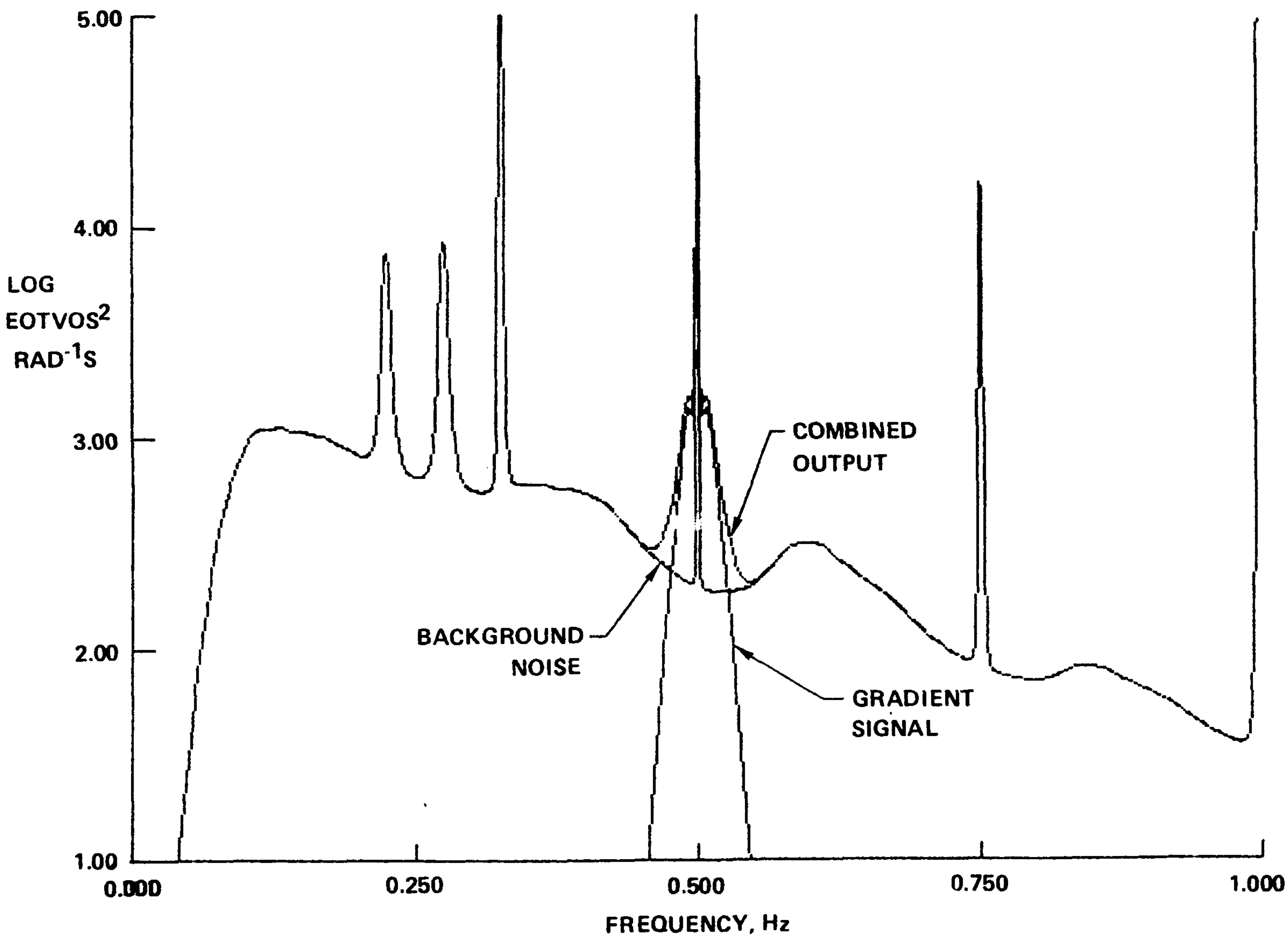
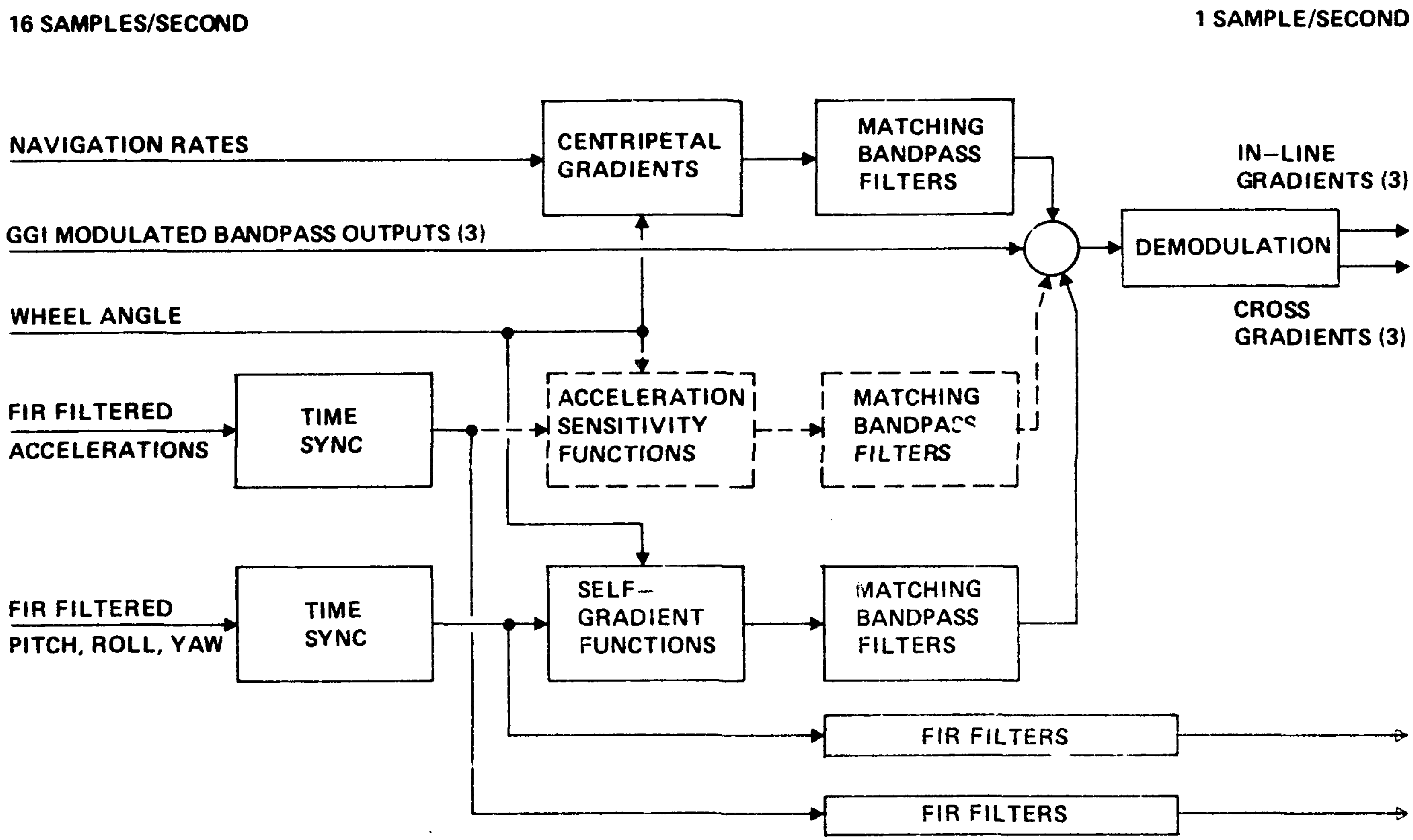
BELL GRADIOMETER OUTPUT CHARACTERISTICS

- EACH INSTRUMENT MEASURES GRADIENTS ALONG 2 AXES
- OUTPUT IS A SUM OF SINE AND COSINE 0.5 Hz MODULATIONS OF GRADIENTS
- INSTANTANEOUS SEPARATE MEASUREMENTS OF GRADIENTS ARE NOT AVAILABLE
- GRADIENTS MUST BE EXTRACTED FROM MEASUREMENTS OVER A TIME PERIOD
- EXTRACTION MUST REJECT NOISE AT OTHER HARMONICS OF 0.25 Hz

MODELLED AIRBORNE GGI OUTPUT SINGLE-SIDED PSD



STAGE 1 PROCESSING



10?

GGSS DEMODULATORS

BUTTERWORTH FILTER

- INSTANTANEOUS ESTIMATE
- PHASE VARIATION OVER SIGNAL SPECTRUM
- NEED TO REJECT ADJACENT NOISE PEAKS FORCES NARROW BANDWIDTH (0.025 Hz)
- SUITABLE FOR LOW FREQUENCY SIGNALS

FINITE SAMPLE SET ESTIMATOR

- DELAYED ESTIMATES
- NO PHASE VARIATIONS
- BANDWIDTH MATCHED TO SIGNAL STATISTICS
- MATCHED REJECTION OF ADJACENT NOISE
- PERMITS ESTIMATION OF HIGH FREQUENCY SIGNALS

DEMODULATING ESTIMATOR

ESTIMATE 2 GRADIENT SIGNALS AT 1 SECOND INTERVALS FROM A SUM OF SINE AND COSINE MODULATIONS AT 1/16 SECOND SAMPLE INTERVALS + RANDOM NOISE + SIGNALS MODULATED AT OTHER HARMONICS

MINIMIZING MEAN SQUARE ERROR:

$$\underset{\text{ESTIMATE}}{\hat{\underline{x}}} = \underbrace{\langle \underline{x}\,\underline{x}^t \rangle \; H^t \; \langle \underline{z}\,\underline{z}^t \rangle^{-1}}_{\text{FIXED WEIGHTS}} \; \underset{\text{SAMPLE SET}}{\underline{z}}$$

$\langle \underline{x}\,\underline{x}^t \rangle$: SIGNAL AUTOCORRELATION (ASSUMES STATIONARITY)

H^t: MODULATION & PHASE (DETERMINISTIC)

$\langle \underline{z}\,\underline{z}^t \rangle^{-1}$: NON–STATIONARY SAMPLE COVARIANCE

$\langle\ \rangle$ DENOTES EXPECTATION

- 4 SAMPLE COVARIANCE MATRICES COMPUTED OVER AN EXTENDED PERIOD OF DATA AT 90° PHASE INTERVALS OF 0.25 Hz
- SIGNAL AUTOCORRELATION FOUND BY SUBTRACTING BACKGROUND NOISE FROM MEASUREMENT PSD NEAR 0.5 Hz, SHIFTING TO 0 Hz AND FORCING SYMMETRY
- NEWWEIGHTS NEEDED ONLY WHEN SIGNAL OR NOISE CHARACTERISTICS CHANGE

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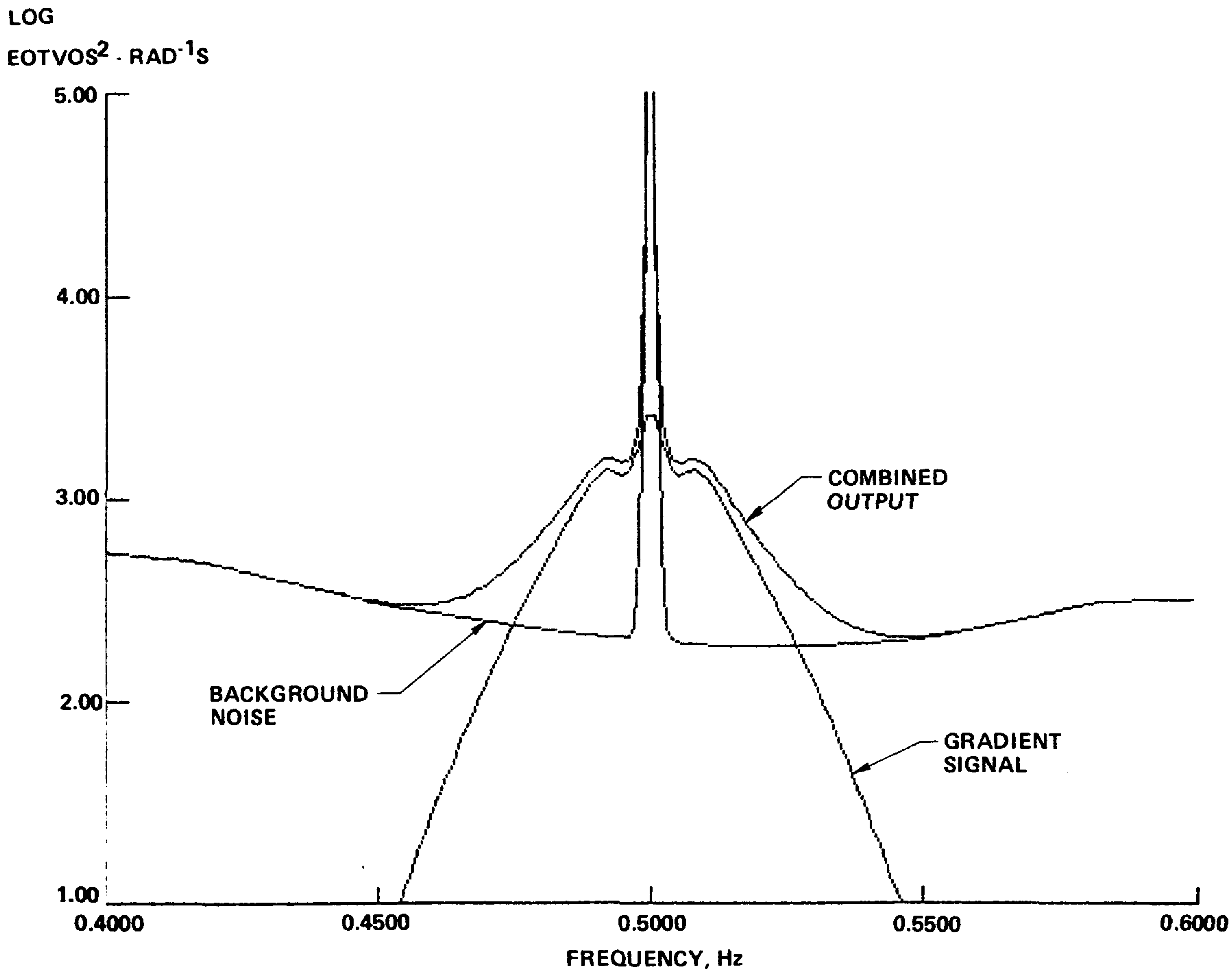
MODELLED AIRBORNE GGI OUTPUT SINGLE-SIDED PSD



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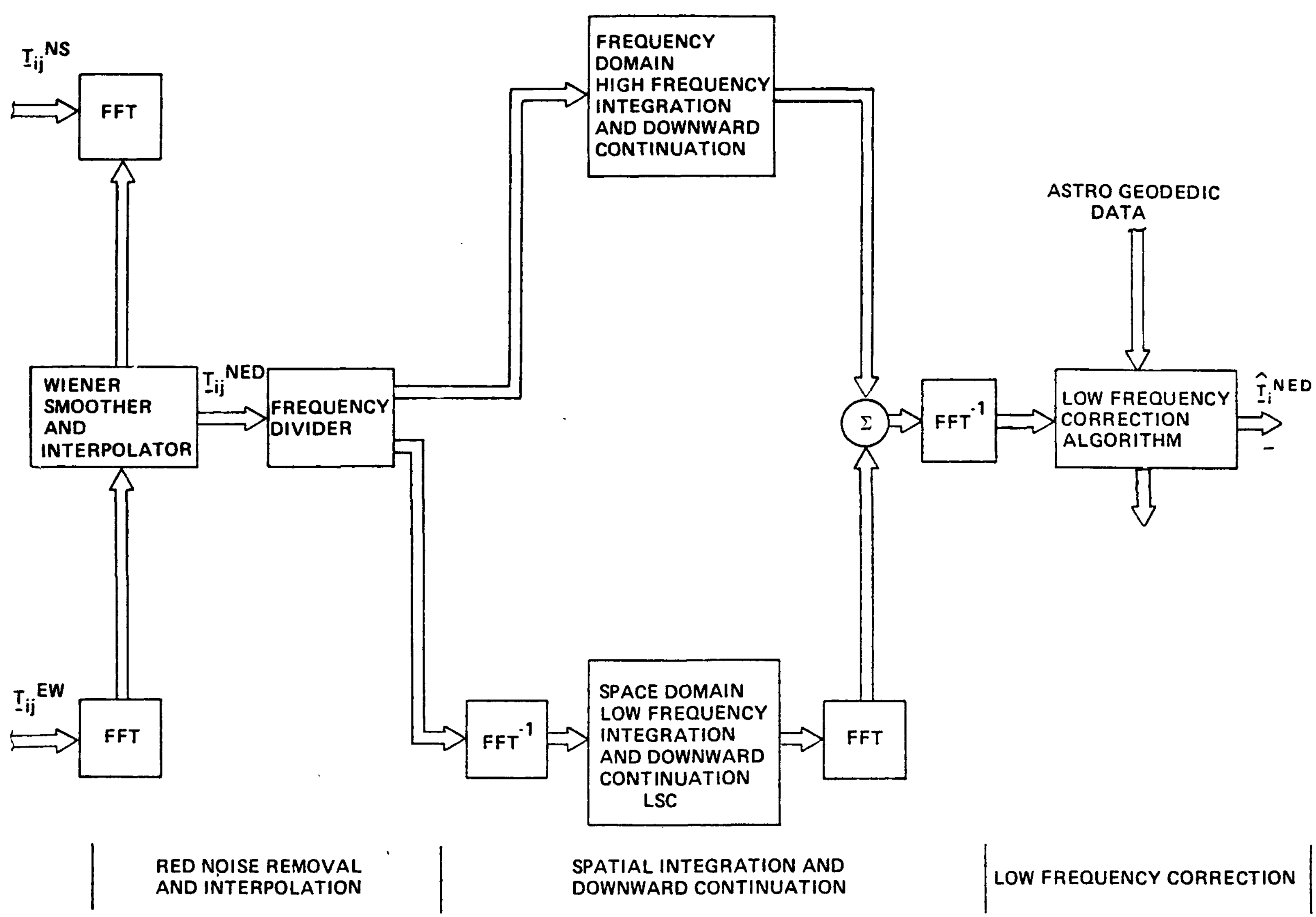
Part 2 - Gravity Survey Data Reduction using Frequency Domain Techniques

An algorithm for estimating the gravity disturbance vector map from gravity gradiometer survey measurements collected on a regular grid is described. The approach implements a complimentary filter which deals with the low spatial frequency components of the data in the space domain (least squares collocation) while the residual data is dealt with in the frequency domain (Wiener smoothing). The algorithm explicitly deals with instrument red noise and simultaneously carries out the integration and downward continuation. The main advantage offered by this approach is computational efficiency.

GGSS STAGE II DATA PROCESSING

REQUIREMENT:	DERIVE GRAVITY DISTURBANCE VECTOR MAP BY SPATIAL INTEGRATION AND DOWNWARD CONTINUATION OF GRAVITY GRADIENT DATA.
FUNDAMENTAL PROBLEM:	LARGE AMOUNT OF DATA OUTPUT FROM STAGE I PROCESSING – 120 X 300 X 6 = 216000 GRADIENT MEASUREMENTS – MAKES OPTIMAL PROCESSING IMPOSSIBLE.
BELL APPROACH:	USE FREQUENCY DOMAIN TECHNIQUES WHERE POSSIBLE AND SPACE DOMAIN TECHNIQUES WHERE REQUIRED.
LIMITATION:	REQUIRES REGULARLY GRIDDED SURVEY PATTERN.
ADVANTAGES:	• COMPUTATIONAL EFFICIENCY • PROVIDES 300 X 300 KM GRAVITY MAP AT 1 KM RESOLUTION IN ONE STAGE

STAGE II PROCESSING



WIENER SMOOTHER STRUCTURE FOR RED NOISE REMOVAL AND GRADIENT INTERPOLATION

MEASUREMENT EQUATION

$$\underline{Z}(\underline{\omega}) = \begin{bmatrix} \underline{T}_{ij}^{EW}(\underline{\omega}) \\ \hline T_{ij}^{NS}(\omega) \end{bmatrix} + \begin{bmatrix} \underline{V}^{EW}(\omega_x) \\ \hline \underline{V}^{NS}(\omega_y) \end{bmatrix}$$

MEASUREMENT POWER SPECTRUM MATRIX

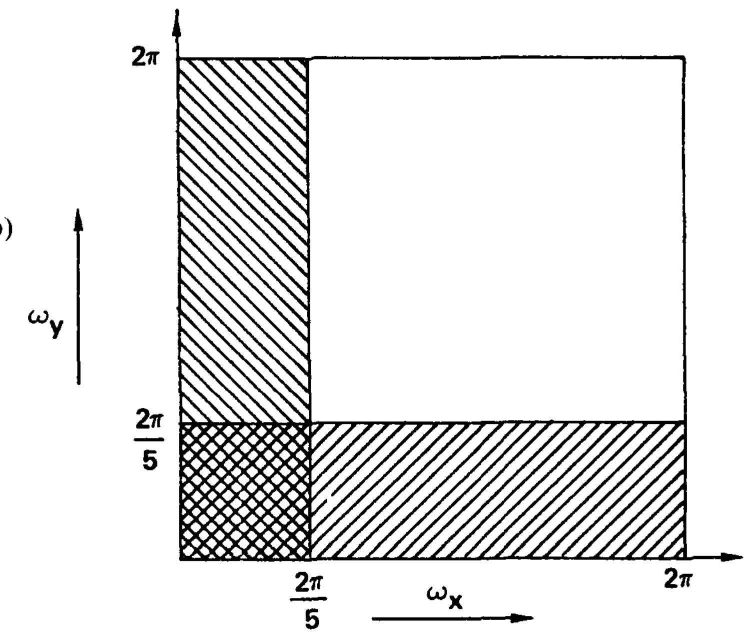
$$S_{\underline{\underline{ZZ}}}'(\underline{\omega}) = \left[\begin{array}{c|c} S_{\underline{T}_{ij}\underline{T}_{ij}}'(\omega) + S_{\underline{\underline{vv}}}^{EW\prime}(\omega_x) & S_{\underline{T}_{ij}\underline{T}_{ij}}'(\underline{\omega}) \\ \hline S_{\underline{T}_{ij}\underline{T}_{ij}}'(\underline{\omega}) & S_{\underline{T}_{ij}\underline{T}_{ij}}'(\underline{\omega}) + S_{\underline{\underline{vv}}}^{NS\prime}(\omega_y) \end{array}\right]$$

GGI NOISE SPECTRUM

$$S_{\underline{\underline{vv}}}^{EW\prime}(\omega_x) = \left[\frac{A}{(\omega_x v)^2} + B\right]\frac{vd}{\pi^2}$$

ESTIMATION EQUATION

$$\hat{\underline{T}}_{ij}(\underline{\omega}) = S_{\underline{T}_{ij}\underline{T}_{ij}}'(\underline{\omega})\, S_{\underline{\underline{zz}}}^{-1\prime}(\underline{\omega})\, \underline{Z}(\underline{\omega})$$



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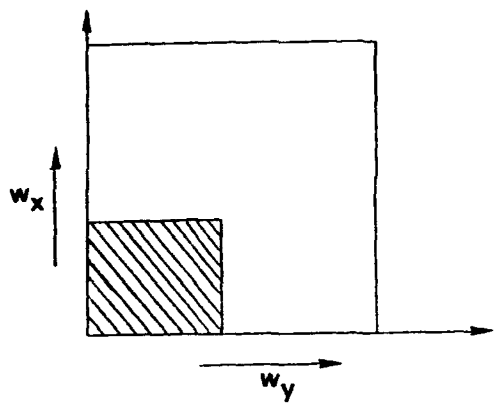
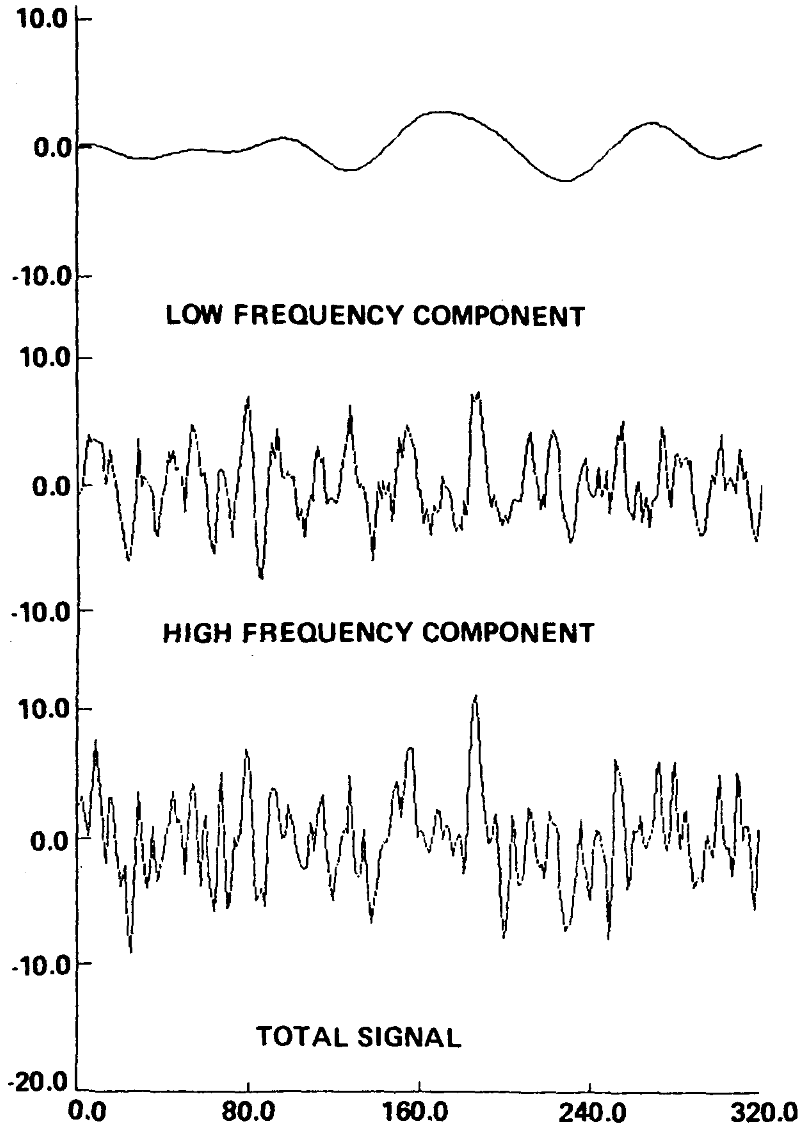
FREQUENCY DIVISION



FREQUENCY PLANE



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INTEGRATION AND DOWNWARD CONTINUATION

LEAST SQUARES COLLOCATION GAIN EQUATION:

$$\hat{G}_{(\underline{r},h)} = E_{\underline{T}_i\underline{T}_{ij}}{}' (\underline{r},\underline{r}^M,h) \left[E_{\underline{T}_{ij}\underline{T}_{ij}}{}' (\underline{r}^M) + E_{\underline{n}\underline{n}}{}' \right]^{-1}$$

WIENER SMOOTHER GAIN EQUATION:

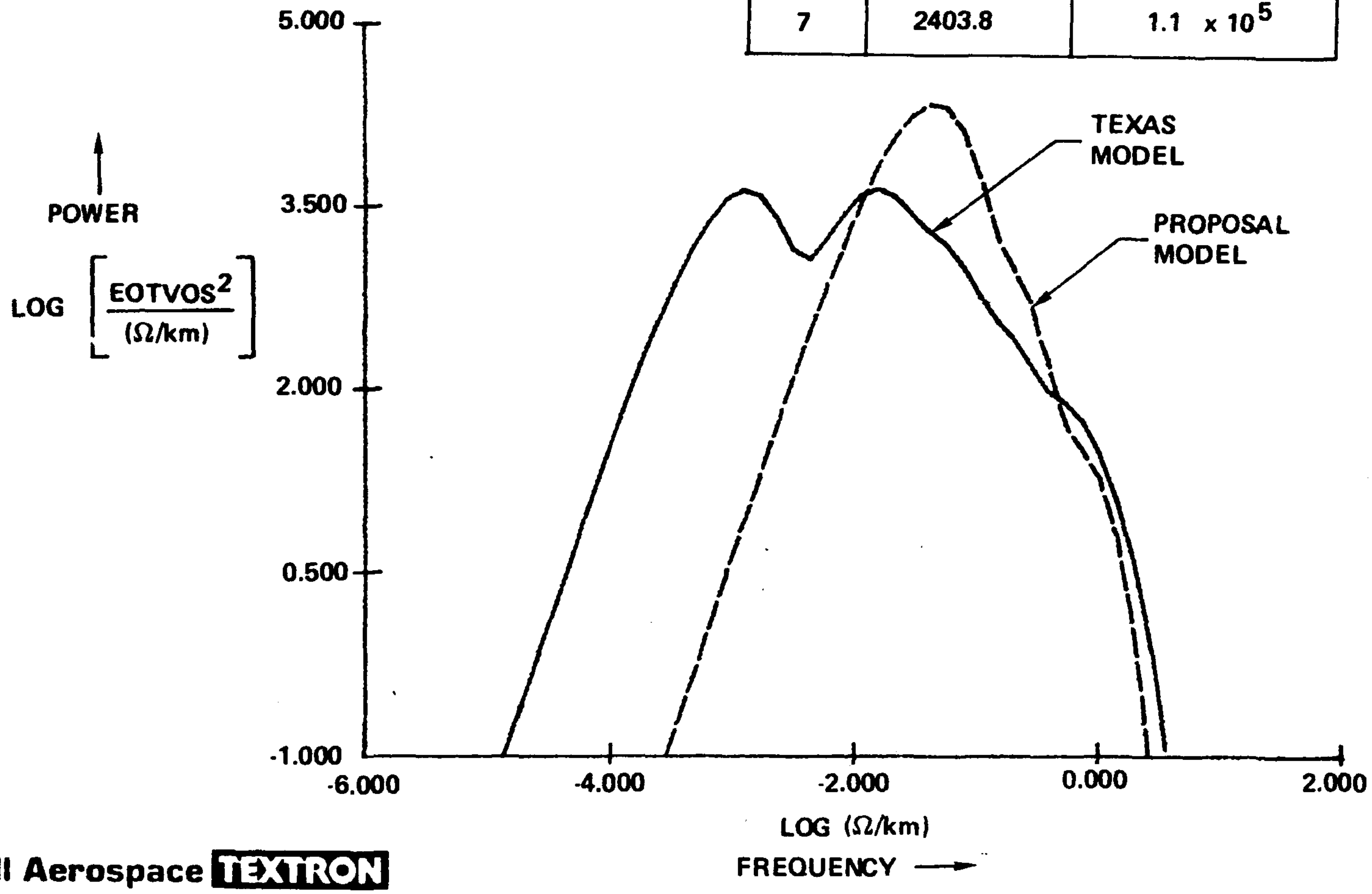
$$\hat{G}_{(\underline{\omega},h)} = S_{\underline{T}_i\underline{T}_{ij}}{}' (\underline{\omega},h) \left[S_{\underline{T}_{ij}\underline{T}_{ij}}{}' (\underline{\omega}) + S_{\underline{n}\underline{n}}{}' \right]^{-1}$$

WHERE h IS SURVEY ALTITUDE.

GRAVITY FIELD PSD

$$S_{T_zT_z'} = \sum_{i=1}^{7} \frac{2\pi\, \sigma_i^2 \omega}{\alpha_i}\, e^{-\frac{\omega}{\alpha_i}}$$

i	$\frac{1}{\alpha_i}$ (km)	σ_i (m^4/s^4)
1	3.3	7.5×10^{-4}
2	6.6	1.42×10^{-2}
3	22.22	7.5×10^{-1}
4	68.96	3.6×10^{3}
5	204.1	7.78×10^{2}
6	1298.7	3.5×10^{3}
7	2403.8	1.1×10^{5}



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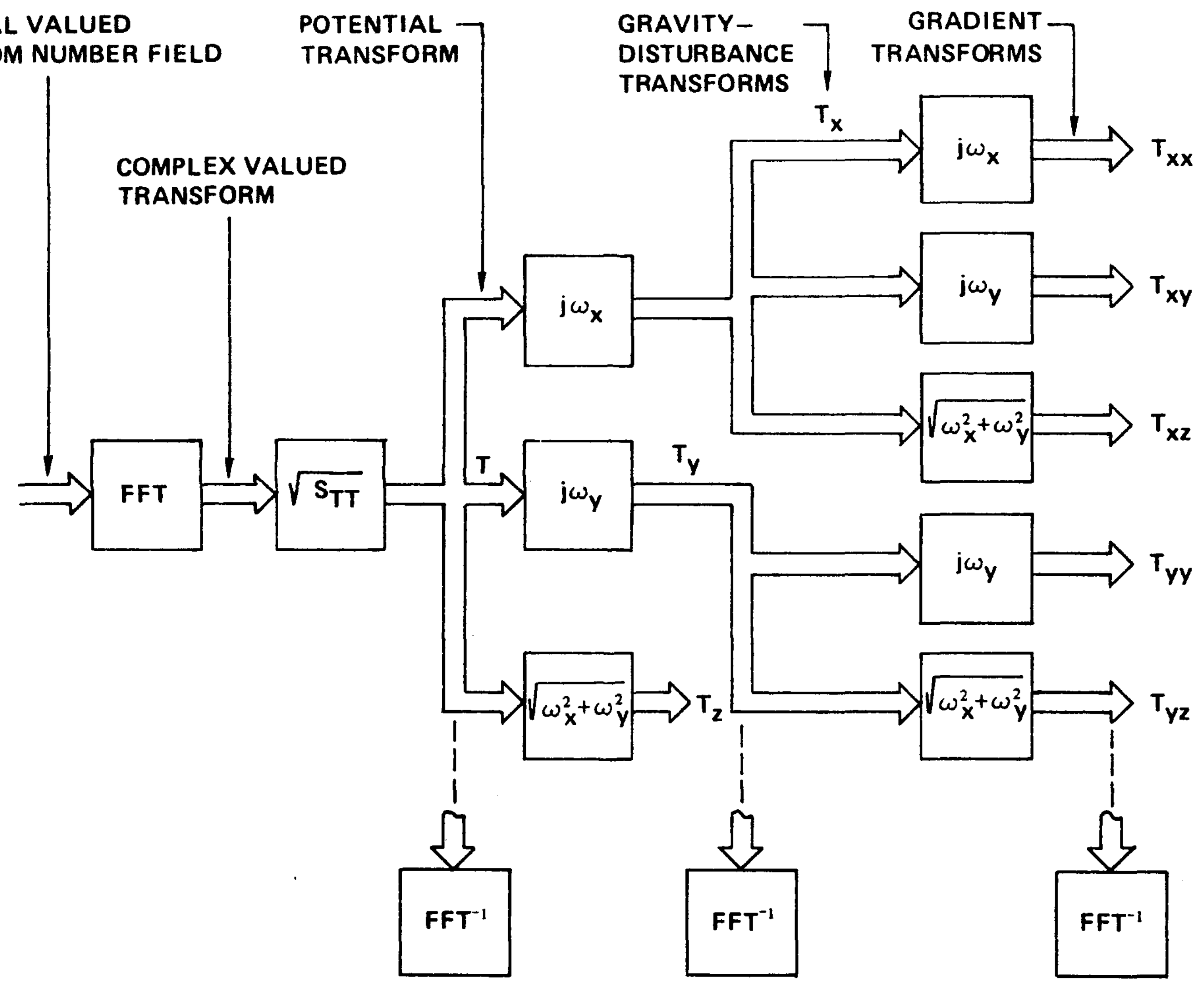
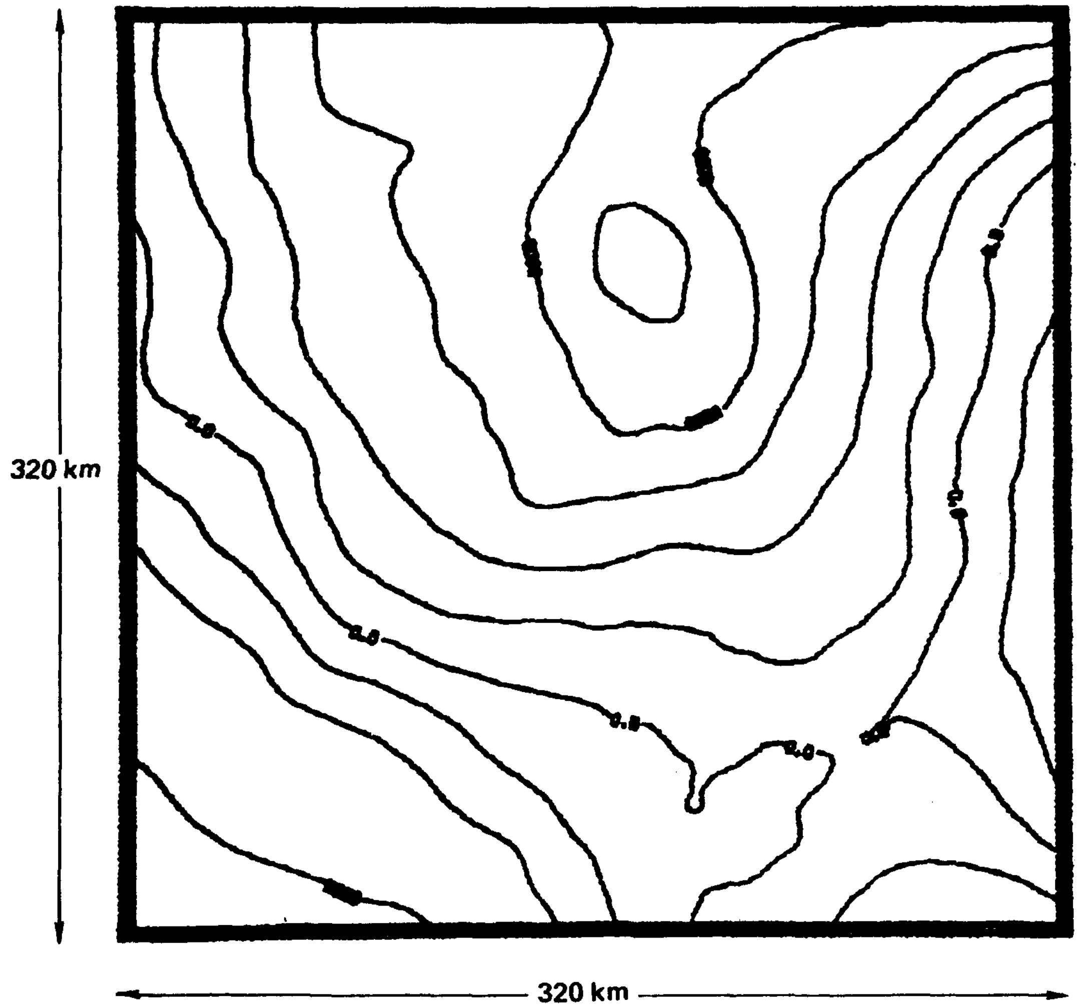
SYNTHETIC GRAVITY FIELD GENERATION



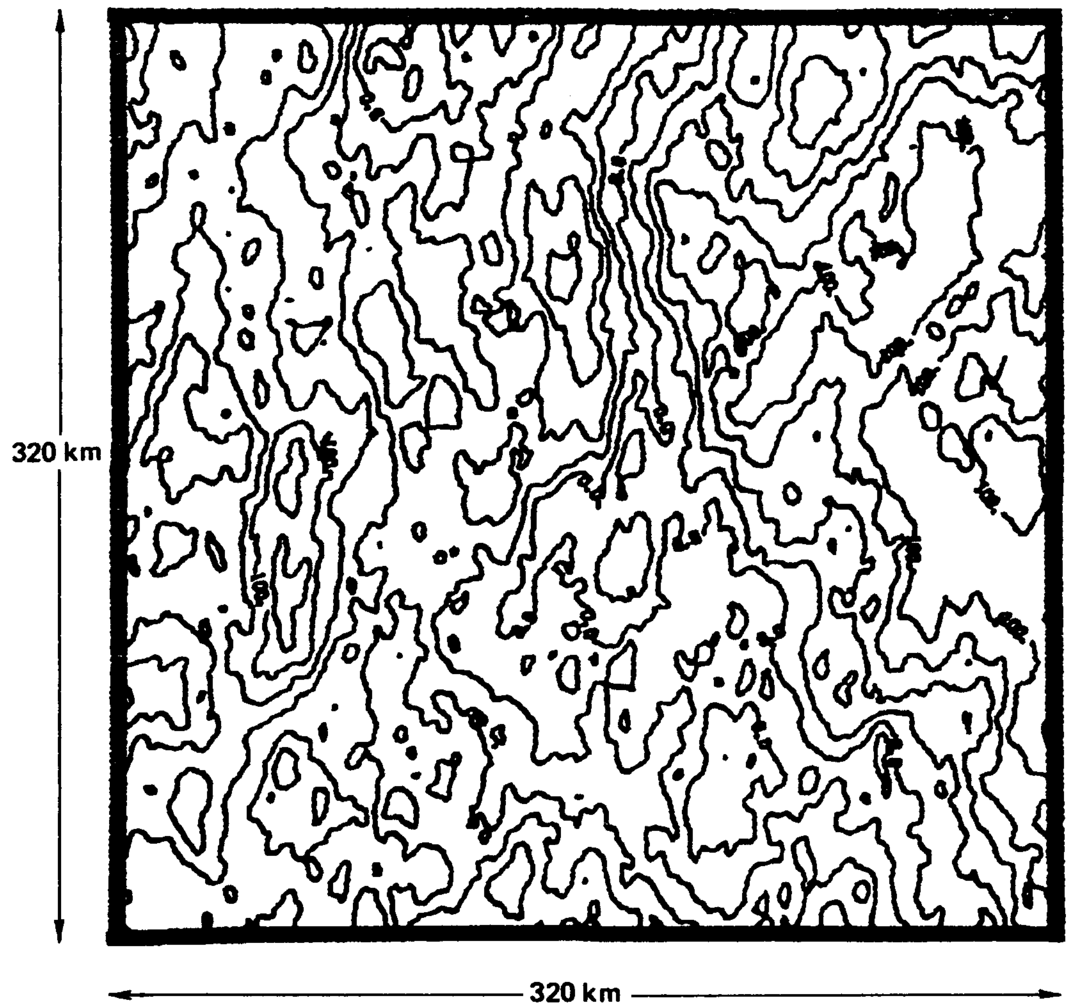
SYNTHETIC FIELD POTENTIAL CONTOUR MAP

CONTOUR INTERVAL 2000 E km^2



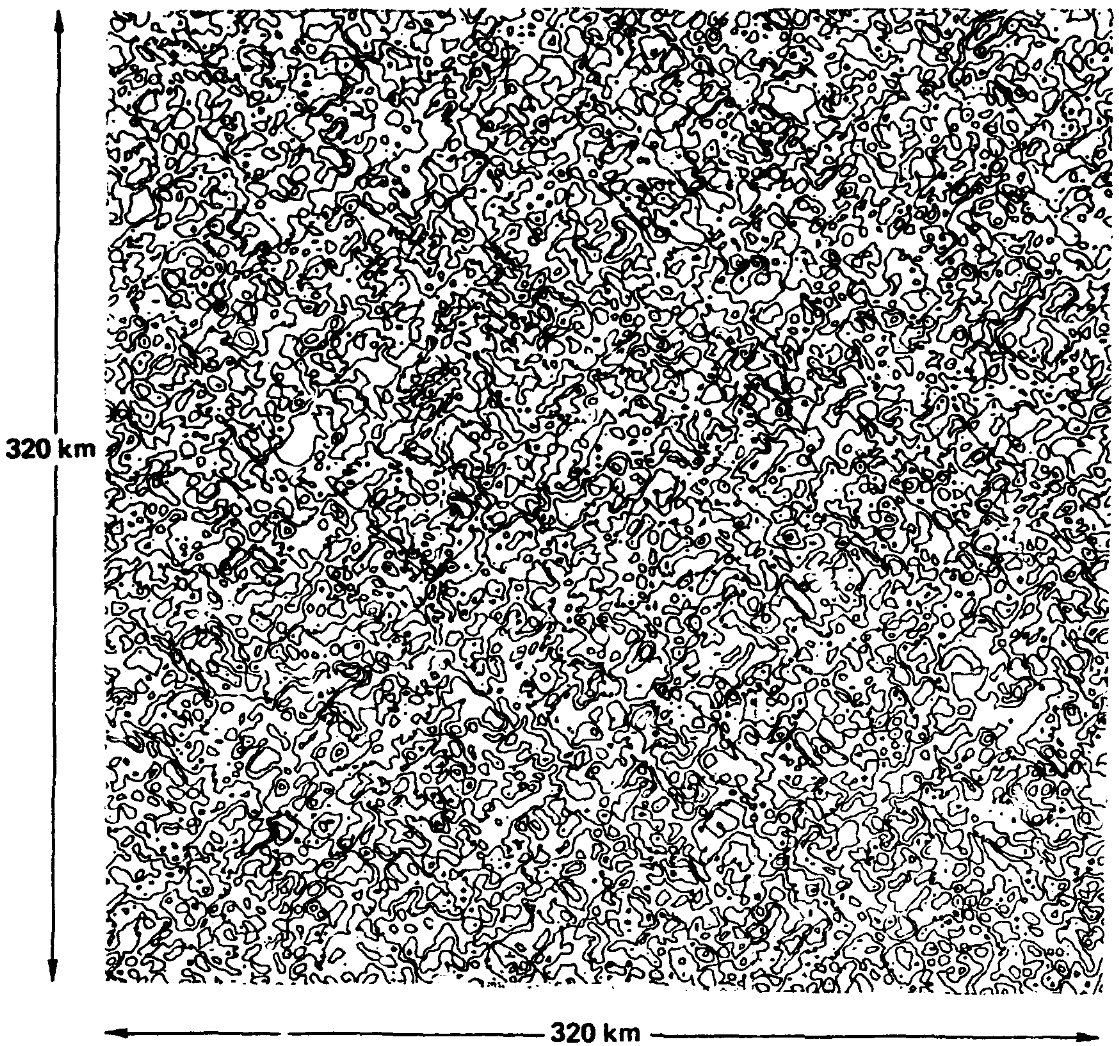
SYNTHETIC FIELD VERTICAL DEFLECTION (T_x) CONTOUR MAP

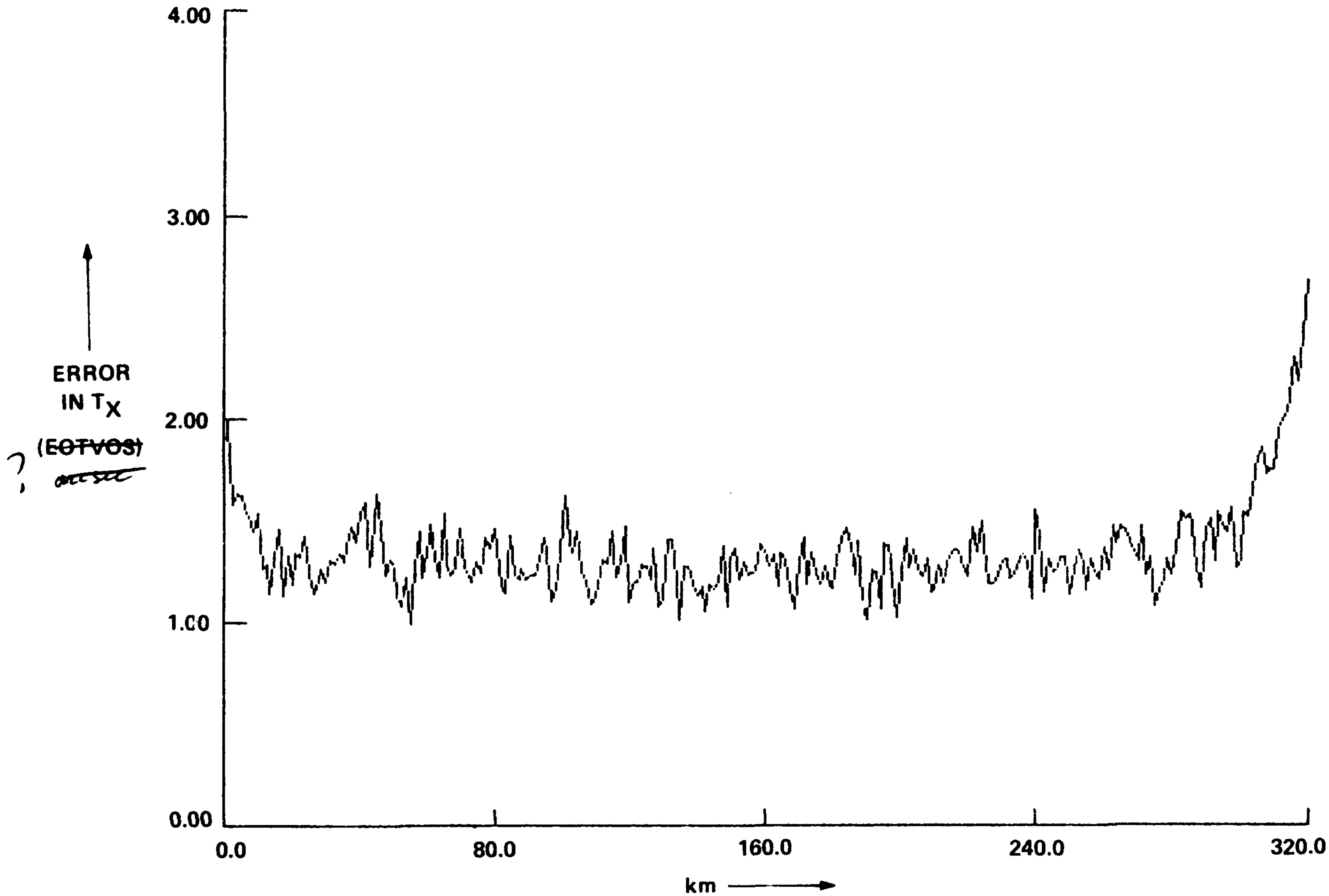
CONTOUR INTERVAL: 1/2 $\hat{SEC}$



SYNTHETIC FIELD GRADIENT (T_{xy}) CONTOUR MAP

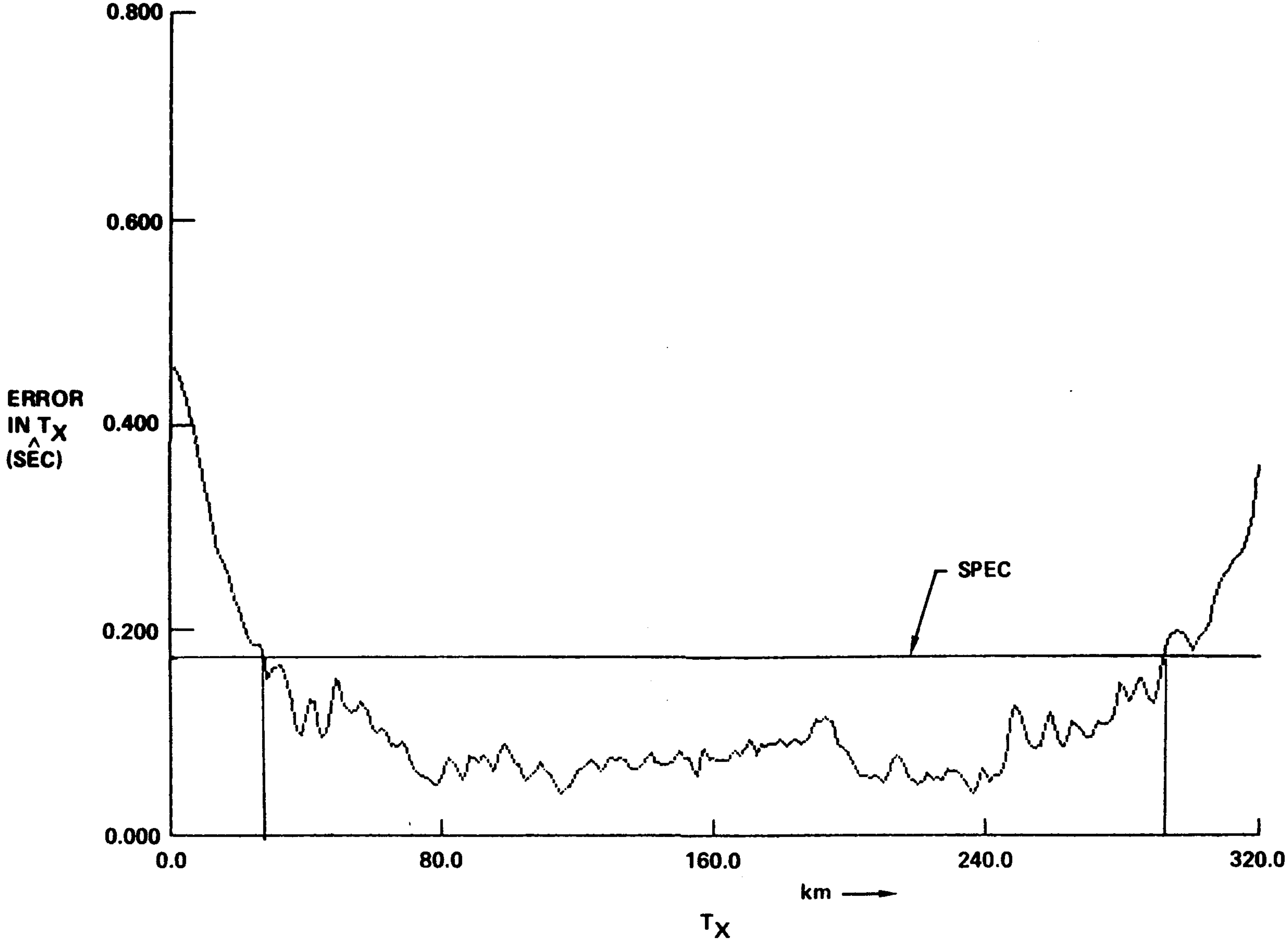
CONTOUR INTERVAL 2 EOTVOS



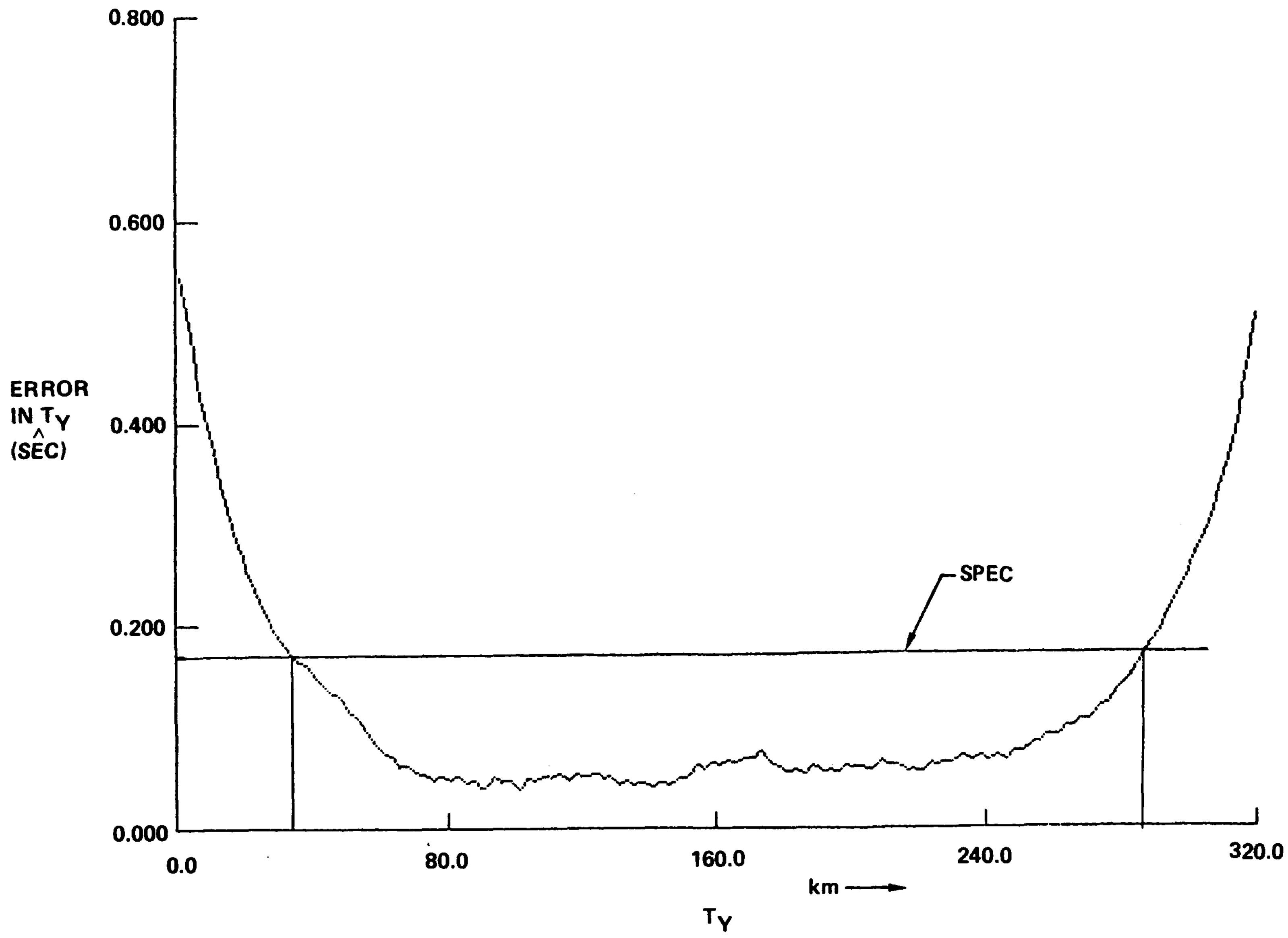


TYPICAL GRADIENT ERROR ALONG ONE TRACK

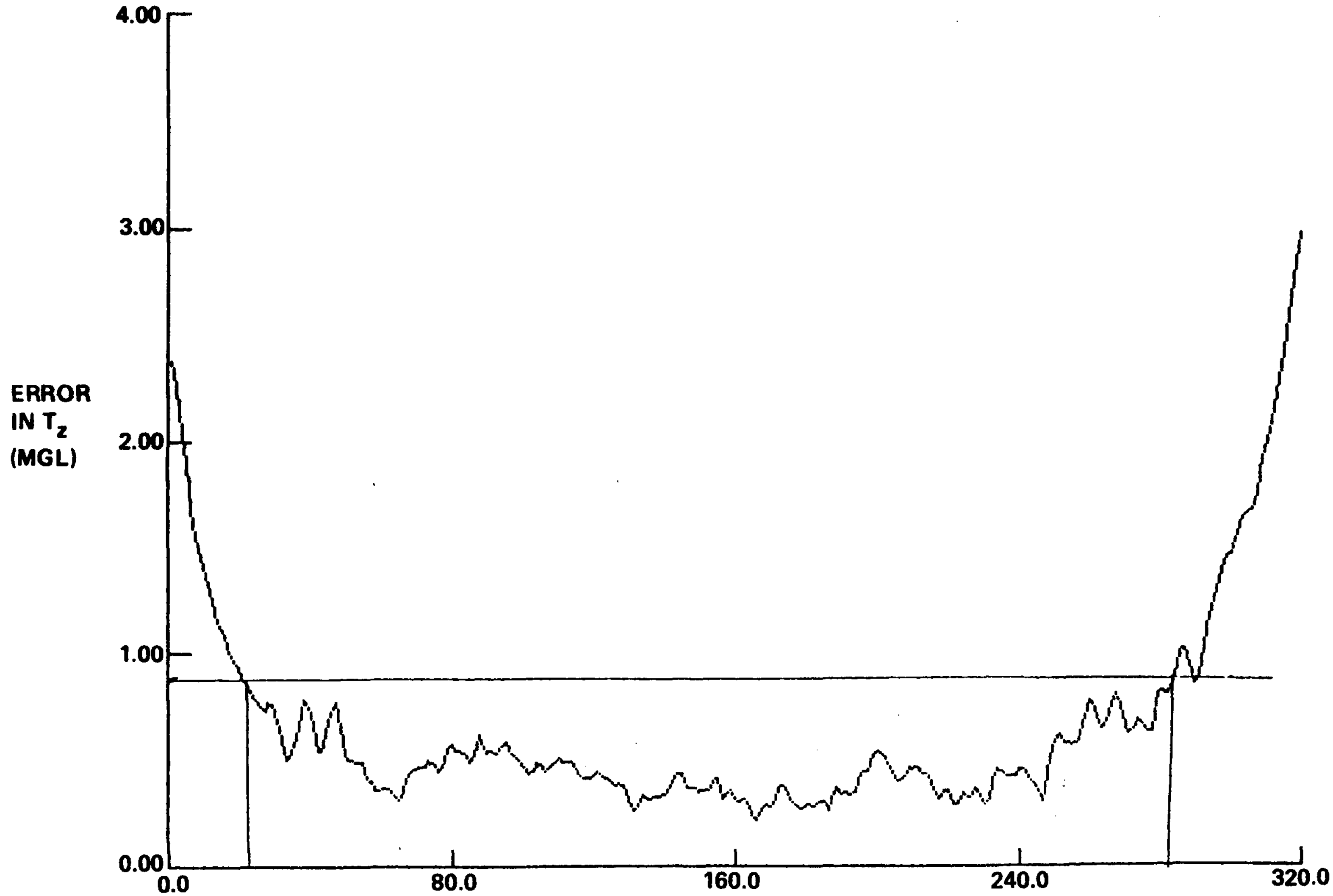
AVERAGE MAP ERROR OF CENTRAL 160 km STRIP



AVERAGE MAP ERROR OF CENTRAL 160 km STRIP



AVERAGE MAP ERROR OF CENTRAL 160 km STRIP



CONCLUSIONS/SUMMARY

- OPTIMAL ESTIMATION OF T_i IS IMPOSSIBLE
- PURE FREQUENCY DOMAIN ESTIMATION OF T_i GIVES UNACCEPTABLY LARGE ERRORS
- BELL HYBRID APPROACH APPEARS TO GIVE GOOD COMPROMISE:
  - LESS THAN TWO HOURS c.p.u. TIME
  - CAN MEET SPEC OVER 75% OF MAP AREA

FUTURE EFFORTS

- INCLUDE DOWNWARD CONTINUATION
- SENSITIVITY STUDIES
- COVARIANCE ANALYSIS
- DATA GRIDDING

Superconducting Accelerometers and Gravity Gradiometers.

Ho Jung Paik
University of Maryland

in collaboration with

H. A. Chan
M. V. Moody
J. W. Parke
D. Hart
Q. Kong

at U. Maryland

E. R. Mapoles
K. Wang
W. M. Fairbank
D. DeBra

at Stanford U.

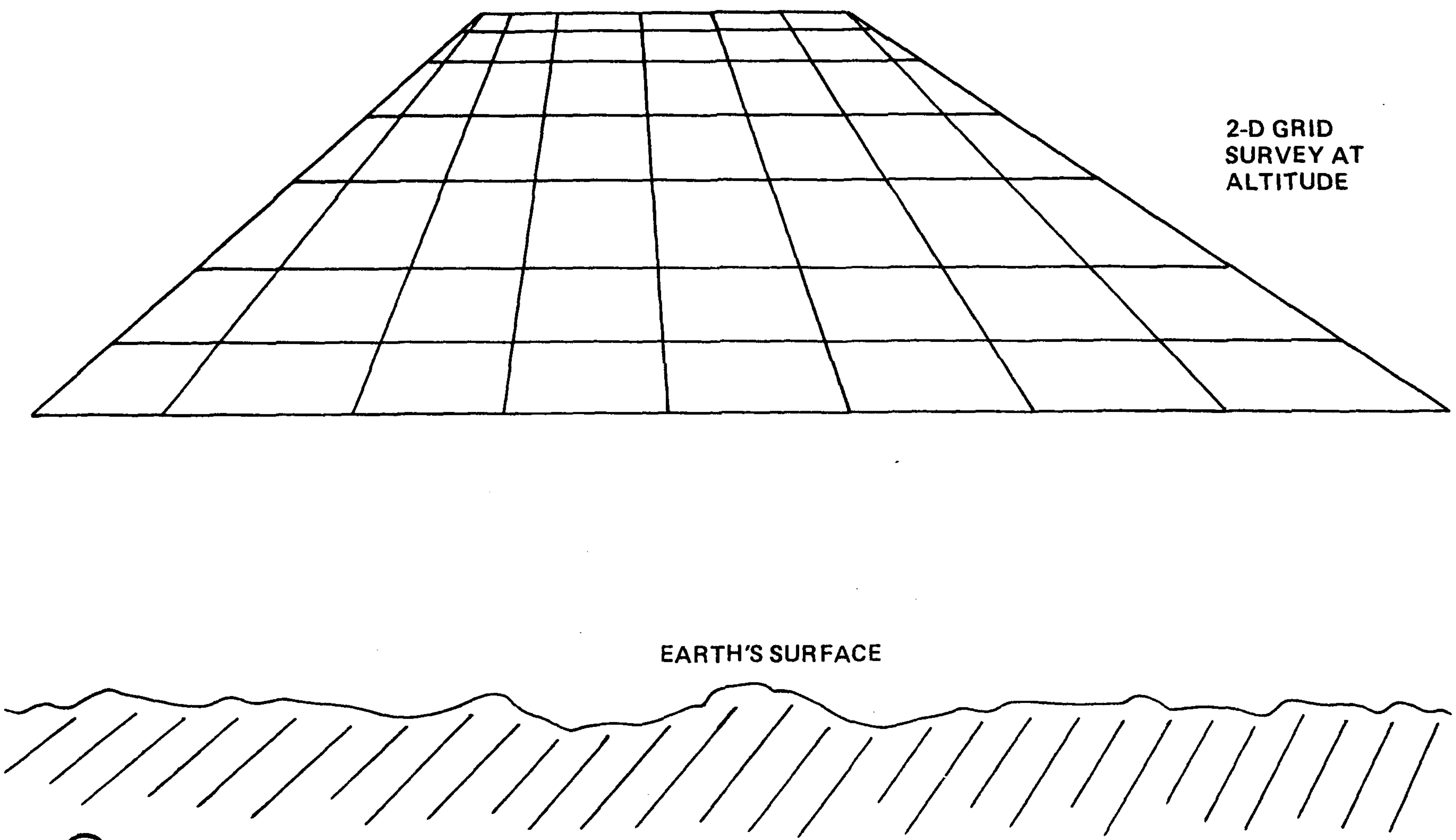
2/12/85

13th Gravity Gradiometer Conference
Colorado Springs, Colorado

OVERVIEW

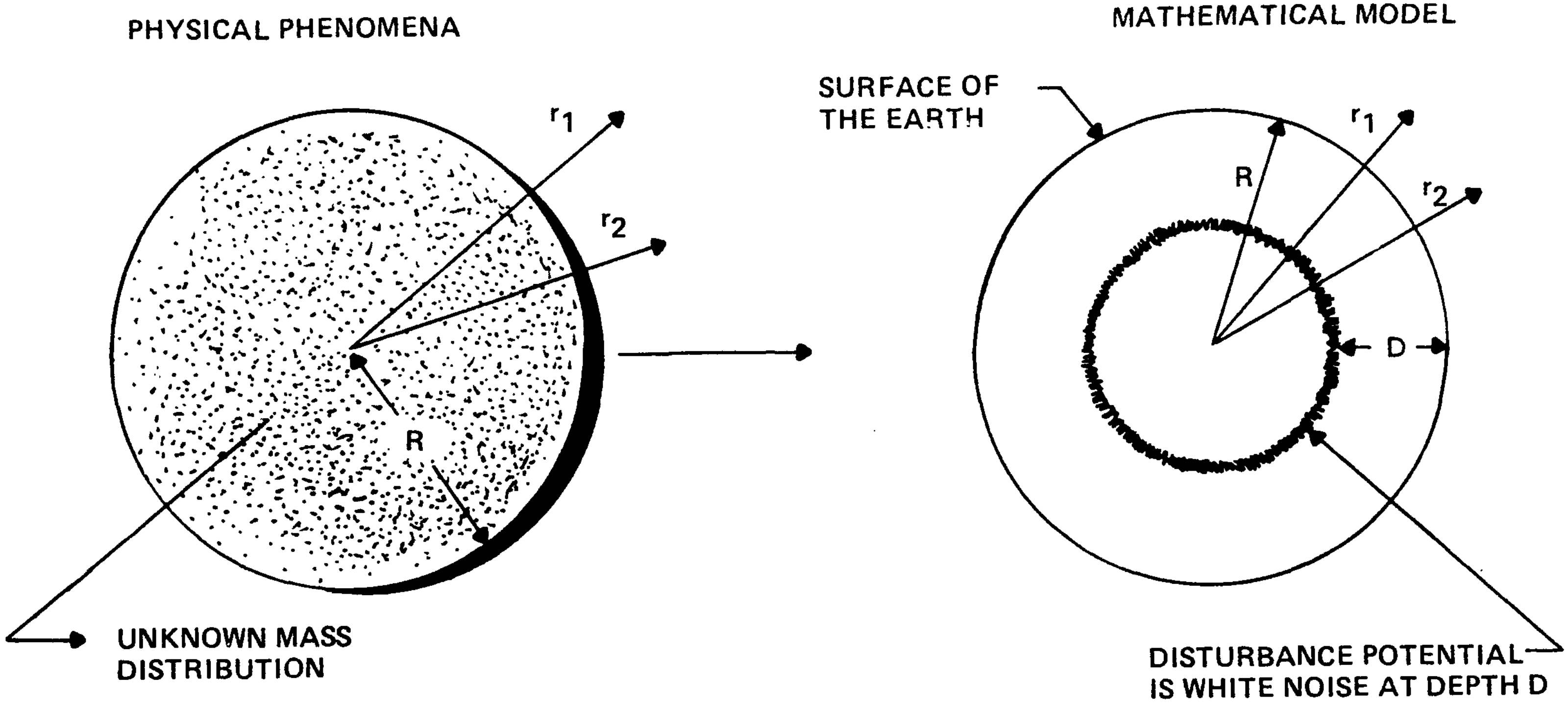
- SURVEY GEOMETRY
- GRAVITY MODEL
- SMOOTHING ALGORITHM
- DISCRETE IMPLEMENTATION
- SUMMARY

AIRBORNE GRAVITY GRADIOMETRIC SURVEYS



APPLIED SCIENCE ANALYTICS, INC.

ATTENUATED WHITE NOISE MODEL



$\nabla^2 T = 0 \quad ; \quad r > R \longrightarrow \nabla^2 T = 0 \; ; \; r > 0$

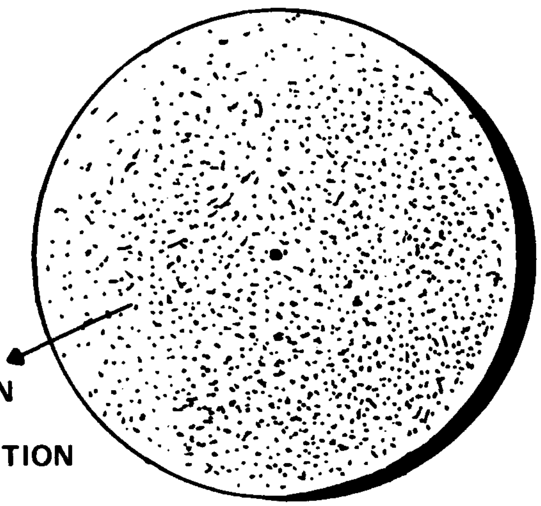
$\nabla^2 T = \rho \quad ; \quad r < R \longrightarrow E\left\{ T(r,\theta_1,\phi_1)\Big|_{@\,r=D} \; T(r,\theta_2,\phi_2)\Big|_{@\,r=D} \right\} = \sigma^2 \delta(\theta_1-\theta_2)\delta(\phi_1-\phi_2) \; ; \; r = D$

$T \longrightarrow 0 \quad ; \quad r \longrightarrow +\infty \longrightarrow T \longrightarrow 0 \quad ; \quad r \longrightarrow \infty$

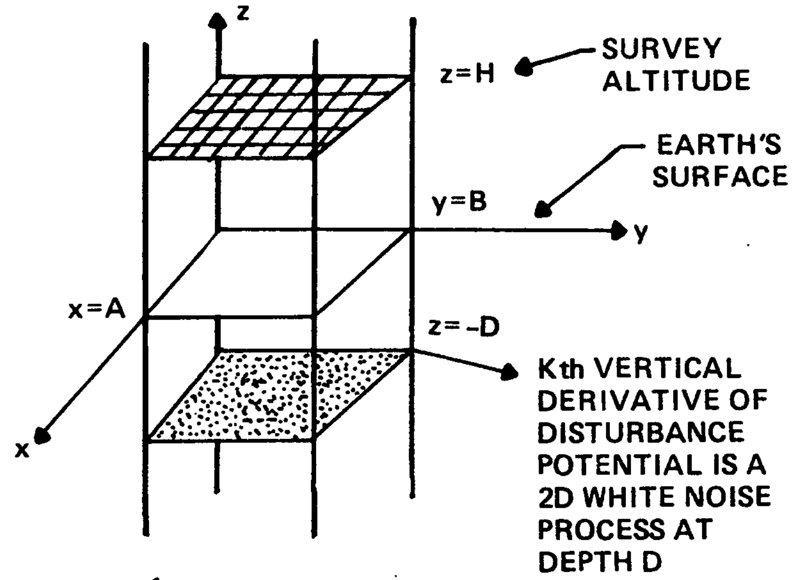
APPLIED SCIENCE ANALYTICS, INC.

LOCAL WHITE NOISE LAYER MODEL

PHYSICAL PHENOMENA



MATHEMATICAL MODEL



$\nabla^2 T = 0$	;	$r > R$	$\longrightarrow$	$\nabla^2 T = 0 \quad \begin{cases} 0 < x < A \\ 0 < y < B \\ -\infty < z < +\infty \end{cases}$
$\nabla^2 T = \rho$	;	$r < R$	$\longrightarrow$	$E\left\{ \left.\frac{\partial^k T}{\partial z^k}(x_1,y_1,z)\right\|_{@\,z=-D} \left.\frac{\partial^k T}{\partial z^k}(x_2,y_2,z)\right\|_{@\,z=-D} \right\} = \sigma_0^2 \delta(x_1-x_2)\delta(y_1-y_2)$
$T \longrightarrow 0$	;	$r \longrightarrow +\infty$	$\longrightarrow$	$T(x, y = 0, z) = f_1(x)$
				$T(x, y = B, z) = f_2(x)$
				$T(x = 0, y, z) = g_1(y)$
				$T(x = A, y, z) = g_2(y)$
				$T(x, y, z = \pm\infty) = 0$

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LINEAR SUPERPOSITION SOLUTION OF DISTURBANCE POTENTIAL

$$T = T_p + T_c$$

- PARTICULAR SOLUTION – T_p
- LAPLACE'S EQUATION

$$\nabla^2 T_p = 0$$

- NON-ZERO SOURCES

$$E\left\{ \left. \frac{\partial^k T_p}{\partial z^k}(x_1,y_1,z) \right|_{@\,z=-D} \times \left. \frac{\partial^k T_p}{\partial z^k}(x_2,y_2,z) \right|_{@\,z=-D} \right\} = \sigma_0^2 \delta(x_1-x_2)\delta(y_1-y_2)$$

$$0 < x_1, x_2 < A$$
$$0 < y_1, y_2 < B$$
$$z = -D$$

- ZERO BOUNDARY CONDITIONS

$T\,(x=0,y,z) = 0$

$T\,(x=A,y,z) = 0$

$T\,(x,y=0,z) = 0$

$T\,(x,y=B,z) = 0$

$T\,(x,y,z=\pm\infty) = 0$

- COMPLEMENTARY SOLUTION – T_c
- LAPLACE'S EQUATION

$$\nabla^2 T_c = 0$$

- ZERO SOURCES

$$T_c = 0 \qquad \begin{array}{l} 0 < x < A \\ 0 < y < B \\ -\infty < z < +\infty \end{array}$$

- NON-ZERO BOUNDARY CONDITIONS

$T\,(x,y=0,z) = f_1(x)$

$T\,(x,y=B,z) = f_2(x)$

$T\,(x=0,y,z) = g_1(y)$

$T\,(x=A,y,z) = g_2(y)$

$T\,(x,y,z=\pm\infty) = 0$

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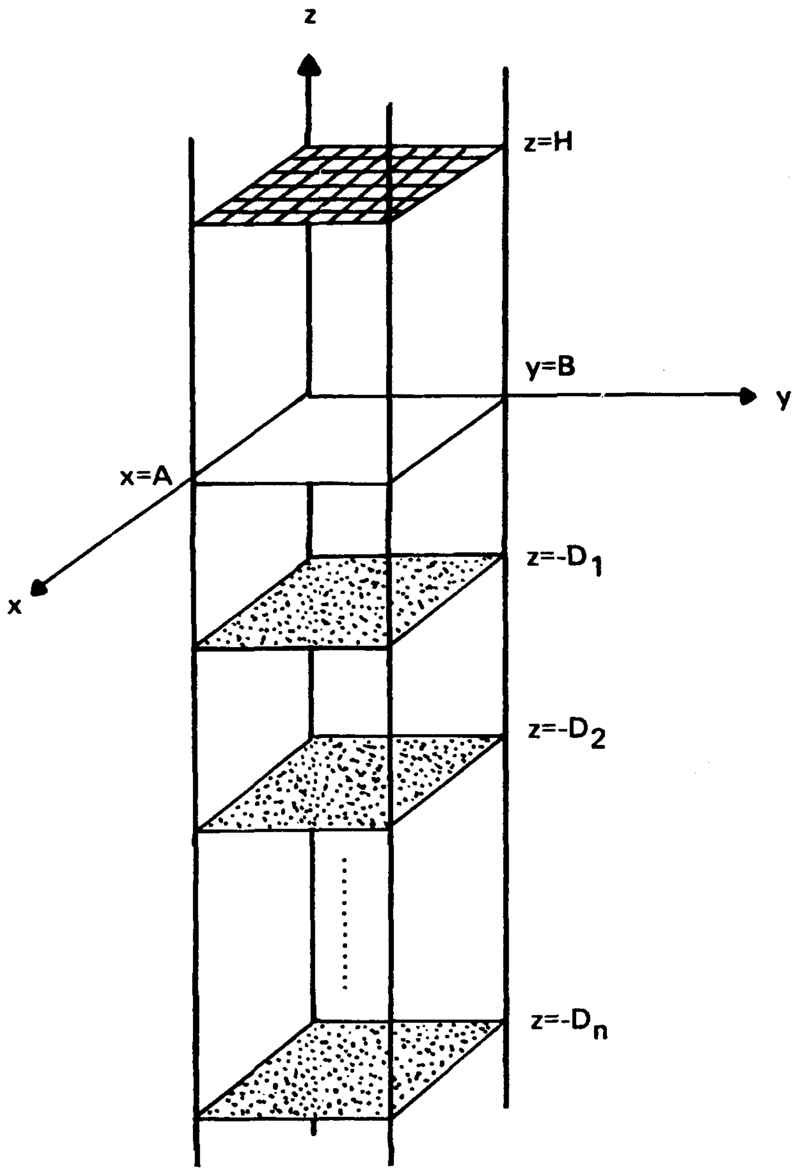
EXTENSION TO MULTIPLE LAYERS



- MODEL CAN ACCOMMODATE MULTIPLE LAYERS OF 2D WHITE NOISE LAYERS
- EACH LAYER CAN MODEL THE VERTICAL DERIVATIVE OF THE DISTURBANCE POTENTIAL TO ANY ORDER

KARHUNEN-LOEVE SERIES REPRESENTATION FOR THE DISTURBANCE POTENTIAL PARTICULAR SOLUTION

- ORTHONORMAL SERIES SOLUTION OF DISTURBANCE POTENTIAL

$$T(x,y,z) = \frac{2}{\sqrt{AB}} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} a_{mn} \sin(a_m x) \sin(b_n y)\, e^{-(a_m^2 + b_n^2)^{1/2} |z-D|}$$

$$a_m = \frac{m\pi}{A} \quad ; \quad b_n = \frac{n\pi}{B}$$

- UNCORRELATEDNESS OF EXPANSION COEFFICIENTS

$$E\left\{a_{mn}\, a_{m'n'}\right\} \triangleq \lambda_{mn}\, \delta_{mm'}, \delta_{nn'}$$

- 2D WHITE NOISE MODEL FOR kth VERTICAL DERIVATIVE OF DISTURBANCE POTENTIAL

$$\lambda_{mn} = \frac{\sigma_0^2\, e^{4D(a_m^2 + b_n^2)^{1/2}}}{(a_m^2 + b_n^2)^k}$$

A – LENGTH OF SURVEY REGION
B – WIDTH OF SURVEY REGION
D – DEPTH OF WHITE NOISE LAYER
σ_0^2 – VARIANCE OF WHITE NOISE
k – ORDER OF VERTICAL DERIVATIVE OF T
H – HEIGHT OF SURVEY ABOVE EARTH'S SURFACE

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NON-ISOTROPIC, NON-STATIONARY DISTURBANCE POTENTIAL COVARIANCE

$$R_{TT}(x_1,y_1,z_1\,;x_2,y_2,z_2) = E\left\{T(x_1,y_1,z_1)\,T(x_2,y_2,z_2)\right\}$$

$$= \frac{4}{AB}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\lambda_{mn}\sin(a_m x_1)\sin(b_n y_1)\sin(a_m x_2)\sin(b_n y_2)\times$$

$$\exp\left[-(a_m^2+b_n^2)^{1/2}(z_1+z_2-2D)\right] \quad ; \quad \begin{array}{l} 0 < x_1,x_2 < A \\ 0 < y_1,y_2 < B \\ D < z_1,z_2 < +\infty \end{array}$$

GRAVITY GRADIENT MEASUREMENT TENSOR

$$Z(x,y,z) = S(x,y,z) + V(x,y,z) \quad ; \quad 0 < x < A \;;\; 0 < y < B \;;\; z = H$$

$$S(x,y,H) = \begin{bmatrix} \dfrac{\partial^2 T}{\partial x^2} \\[2ex] \dfrac{\partial^2 T}{\partial y^2} \\[2ex] \dfrac{\partial^2 T}{\partial x \partial y} \\[2ex] \dfrac{\partial^2 T}{\partial x \partial z} \\[2ex] \dfrac{\partial^2 T}{\partial y \partial z} \end{bmatrix} = \begin{bmatrix} \dfrac{-2\pi^2}{A^2\sqrt{AB}} \displaystyle\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} a_{mn}\, m^2 \exp\left\{-\left|H-D\right| \left(a_m^2+b_n^2\right)^{1/2}\right\} \sin(a_m x)\sin(b_n y) \\[2ex] \dfrac{-2\pi^2}{B^2\sqrt{AB}} \displaystyle\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} a_{mn}\, n^2 \exp\left\{-\left|H-D\right| \left(a_m^2+b_n^2\right)^{1/2}\right\} \sin(a_m x)\sin(b_n y) \\[2ex] \dfrac{2\pi^2}{AB\sqrt{AB}} \displaystyle\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} a_{mn}\, mn \exp\left\{-\left|H-D\right| \left(a_m^2+b_n^2\right)^{1/2}\right\} \cos(a_m x)\cos(b_n y) \\[2ex] \dfrac{-2\pi \mathrm{Sgn}(H-D)}{A\sqrt{AB}} \displaystyle\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} a_{mn}\, m \left(a_m^2+b_n^2\right)^{1/2} \exp\left\{-\left|H-D\right| \left(a_m^2+b_n^2\right)^{1/2}\right\} \cos(a_m x)\sin(b_n y) \\[2ex] \dfrac{-2\pi \mathrm{Sgn}(H-D)}{B\sqrt{AB}} \displaystyle\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} a_{mn}\, n \left(a_m^2+b_n^2\right)^{1/2} \exp\left\{-\left|H-D\right| \left(a_m^2+b_n^2\right)^{1/2}\right\} \sin(a_m x)\cos(b_n y) \end{bmatrix}$$

$$= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\sum_{i=1}^{5} a_{mn}\,\psi_{mni}$$

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ORTHOGONALITY OF BASIS FUNCTIONS

$$\int_{x=0}^{x=A} \int_{y=0}^{y=B} \psi_{mn}^{T}(x,y,z)\, \psi_{m'n'}(x,y,z)\, dxdy = \left[2\left(a_m^2 + b_n^2\right)^2 - a_m b_n\right] \exp\left\{-2\left|z-D\right| \left(a_m^2 + b_n^2\right)^{1/2}\right\} \delta_{mm'} \delta_{nn'}$$

$$\psi_{mn}(x,y,z) = \sum_{i=1}^{5} \psi_{mni}(x,y,z)$$

$$\int_{x=0}^{x=A} \int_{y=0}^{y=B} \psi_{mni}^{T}(x,y,z)\, \psi_{m'n'i'}(x,y,z) = \epsilon_{mni}\, \delta_{mm'} \delta_{nn'} \delta_{ii'}$$

$$\epsilon_{mn1} = a_m^4$$

$$\epsilon_{mn2} = b_n^4$$

$$\epsilon_{mn3} = a_m^2\, b_n^2$$

$$\epsilon_{mn4} = a_m^2 \left(a_m^2 + b_n^2\right)$$

$$\epsilon_{mn5} = b_n^2 \left(a_m^2 + b_n^2\right)$$

THE TWO-DIMENSIONAL SMOOTHING ALGORITHM

- LINEAR MEAN SQUARE ESTIMATION CRITERION

$$J = E\left\{\left|a_{mn} - \hat{a}_{mn}\right|^2\right\}$$

- OPTIMAL ESTIMATE USING ALL MEASUREMENTS

$$\hat{a}_{mn} = E\left\{a_{mn}/Z(x,y,z) \quad ; \quad 0 < x < A, 0 < y < B, z = H\right\}$$

- LINEAR ESTIMATOR FOR KARHUNEN-LOEVE COEFFICIENTS

$$\hat{a}_{mn} = \int_{x=0}^{x=A} \int_{y=0}^{y=B} Z^T(x,y,H)\, K_{mn}(x,y,H)\, dxdy$$

- ORTHOGONAL BASIS FUNCTION REPRESENTATION OF GAINS

$$K_{mn}(x,y,H) = \sum_{m'=1}^{\infty} \sum_{n'=1}^{\infty} \sum_{i=1}^{5} \beta^{mn}_{m'n'i}\, \psi_{m'n'i}(x,y,H)$$

DERIVATION OF ESTIMATOR GAINS

- MEASUREMENT NOISE AND SIGNAL UNCORRELATED

$$E\left\{V(x_1,y_1,z_1)\,S^T(x_2,y_2,z_2)\right\} = 0 \Longrightarrow E\left\{V(x_1,y_1,z_1)\,a_{mn}\right\} = 0$$

- ORTHOGONALITY PRINCIPLE OF LINEAR MEAN SQUARE ESTIMATION

$$E\left\{Z(x_1,y_1,H)\,a_{mn}\right\} = E\left\{Z(x_1,y_1,H)\,\hat{a}_{mn}\right\}$$

- INTEGRAL EQUATION FOR ESTIMATOR GAINS

$$\int_{x_2=0}^{x_2=A}\int_{y_2=0}^{y_2=B}\left[R_{SS}(x_1,y_1,H;x_2,y_2,H)+R_{VV}(x_1,y_1,H;x_2,y_2,H)\right]K_{mn}(x_2,y_2,H)\,dx_2dy_2=\lambda_{mn}\psi_{mn}(x_1,y_1,H)$$

- UNIQUE SOLUTION FOR ESTIMATOR GAINS

$$\beta^{mn}_{m'n'i} = \beta^{mn}_{mni}\,\delta_{mm'}\,\delta_{nn'}$$

$$K_{mn}(x,y,H) = \sum_{i=1}^{5}\beta^{mn}_{mni}\,\psi_{mni}(x,y,H)$$

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FORMULATION OF MEASUREMENT INTEGRALS

$$\hat{a}_{mn} = \gamma_{mn1}\beta_{mn1}^{mn}\tilde{Z}_1(m,n) + \gamma_{mn2}\beta_{mn2}^{mn}\tilde{Z}_2(m,n) + \gamma_{mn3}\beta_{mn3}^{mn}\tilde{Z}_3(m,n) + \gamma_{mn4}\beta_{mn4}^{mn}\tilde{Z}_4(m,n) + \gamma_{mn5}\beta_{mn5}^{mn}\tilde{Z}_5(m,n)$$

$$\tilde{Z}_1 = \int_{x=0}^{x=A}\int_{y=0}^{y=B} Z_1(x,y)\sin(a_m x)\sin(b_n y)\,dxdy$$

$$\tilde{Z}_2 = \int_{x=0}^{x=A}\int_{y=0}^{y=B} Z_2(x,y)\sin(a_m x)\sin(b_n y)\,dxdy$$

$$\tilde{Z}_3 = \int_{x=0}^{x=A}\int_{y=B}^{y=B} Z_3(x,y)\cos(a_m x)\cos(b_n y)\,dxdy$$

$$\tilde{Z}_4 = \int_{x=0}^{x=A}\int_{y=0}^{y=B} Z_4(x,y)\cos(a_m x)\sin(b_n y)\,dxdy$$

$$\tilde{Z}_5 = \int_{x=0}^{x=A}\int_{y=0}^{y=B} Z_5(x,y)\sin(a_m x)\cos(b_n y)\,dxdy$$

APPLICATION OF FOURIER TRANSFORMS

$$Z_1(x,y) = \frac{4}{AB} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \tilde{Z}_1(m,n) \sin(a_m x) \sin(b_n y)$$

$$Z_2(x,y) = \frac{4}{AB} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \tilde{Z}_2(m,n) \sin(a_m x) \sin(b_n y)$$

$$Z_3(x,y) = \frac{4}{AB} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \tilde{Z}_3(m,n) \cos(a_m x) \cos(b_n y)$$

$$Z_4(x,y) = \frac{4}{AB} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \tilde{Z}_4(m,n) \cos(a_m x) \sin(b_n y)$$

$$Z_5(x,y) = \frac{4}{AB} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \tilde{Z}_5(m,n) \sin(a_m x) \cos(b_n y)$$

MATRIX FORMULATION FOR 2D DISCRETE MEASUREMENTS

$$\underset{K\times L}{[Z1]} = \frac{4}{AB}\underset{K\times M}{[SX]}\ \underset{M\times N}{[\tilde{Z}1]}\ \underset{N\times L}{[SY]^T}$$

$$\underset{K\times L}{[Z2]} = \frac{4}{AB}\underset{K\times M}{[SX]}\ \underset{M\times N}{[\tilde{Z}2]}\ \underset{N\times L}{[SY]^T}$$

$$\underset{K\times L}{[Z3]} = \frac{4}{AB}\underset{K\times M}{[CX]}\ \underset{M\times N}{[\tilde{Z}3]}\ \underset{N\times L}{[CY]^T}$$

$$\underset{K\times L}{[Z4]} = \frac{4}{AB}\underset{K\times M}{[CX]}\ \underset{M\times N}{[\tilde{Z}4]}\ \underset{N\times L}{[SY]^T}$$

$$\underset{K\times L}{[Z5]} = \frac{4}{AB}\underset{K\times M}{[SX]}\ \underset{M\times N}{[\tilde{Z}5]}\ \underset{N\times L}{[CY]^T}$$

- K, L – NO. OF MEASUREMENTS IN x,y PLANE
- M,N – NO. OF COEFFICIENTS IN K-L SPACE

BRUTE FORCE APPROACH USING MATRIX INVERSIONS

$$[\widetilde{Z1}] = \frac{AB}{4} [SX]^{-1} [Z1] [SY]^{-1}$$

$$[\widetilde{Z2}] = \frac{AB}{4} [SX]^{-1} [Z2] [SY]^{-1}$$

$$[\widetilde{Z3}] = \frac{AB}{4} [CX]^{-1} [Z3] [CY]^{-1}$$

$$[\widetilde{Z4}] = \frac{AB}{4} [CX]^{-1} [Z4] [SY]^{-1}$$

$$[\widetilde{Z5}] = \frac{AB}{4} [SX]^{-1} [Z5] [CY]^{-1}$$

UTILIZATION OF SPECIAL PROPERTIES OF A TOEPLITZ CIRCULANT MATRIX

$$\underset{K\times K}{[SX]^T}\ \underset{K\times K}{[SX]} = \frac{K+1}{2}\ \underset{K\times K}{[I]}$$

$$\underset{K\times K}{[CX]^T}\ \underset{K\times K}{[CX]} = \frac{K+1}{2}\ \underset{K\times K}{[I]} - \underset{K\times K}{[C]}$$

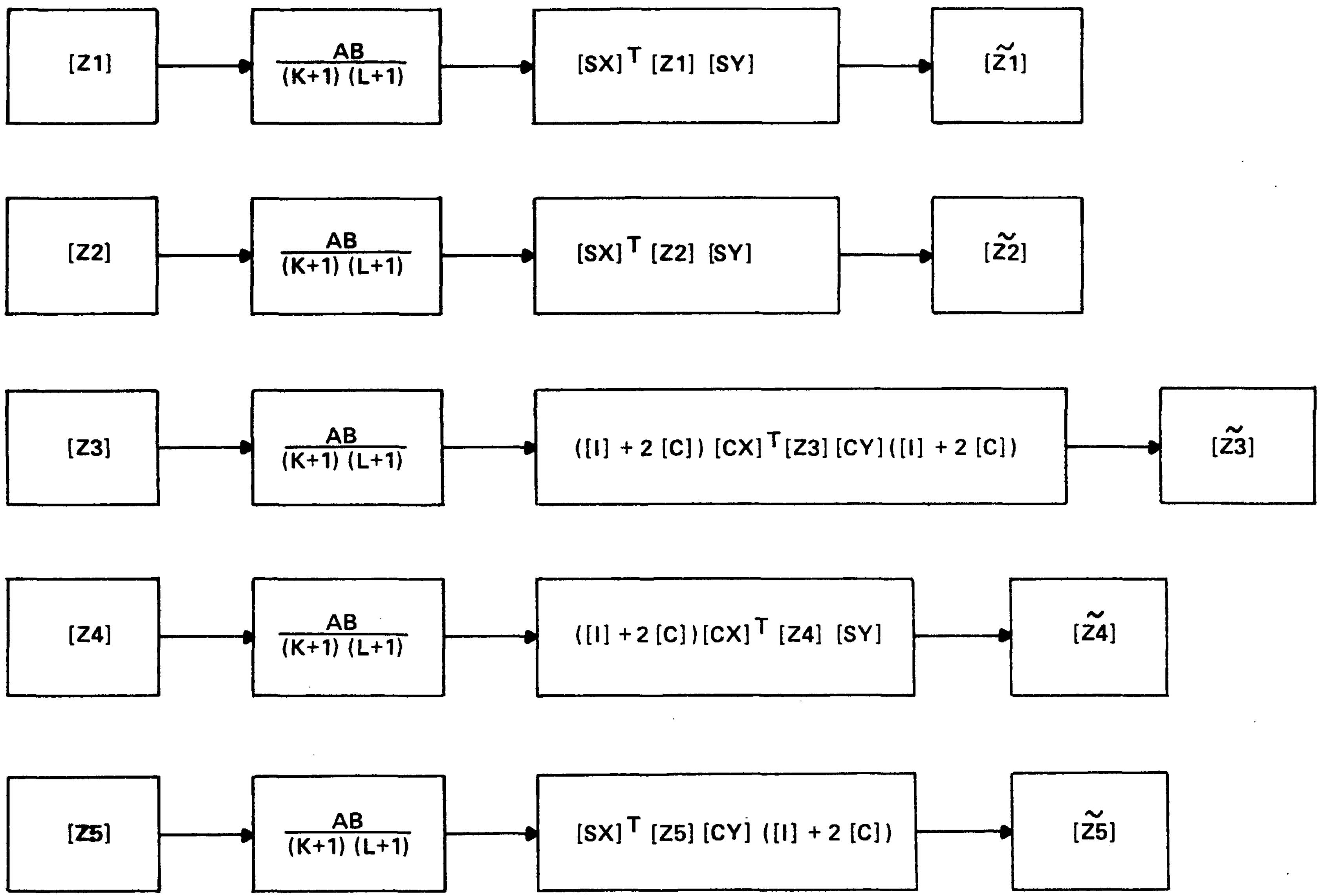
$$\left(\frac{K+1}{2}[I] - [C]\right)^{-1} = \frac{2}{K+1}([I] + 2\,[C]) \quad ; \quad K - \text{even}$$

$$([SX]^T[SX])^{-1} = \frac{2}{K+1}[I]$$

$$([CX]^T[CX])^{-1} = \frac{2}{K+1}([I] + 2\,[C])$$

$$[I] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ; \quad [C] = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}$$

SOLUTION OF MEASUREMENT INTEGRALS WITHOUT MATRIX INVERSIONS



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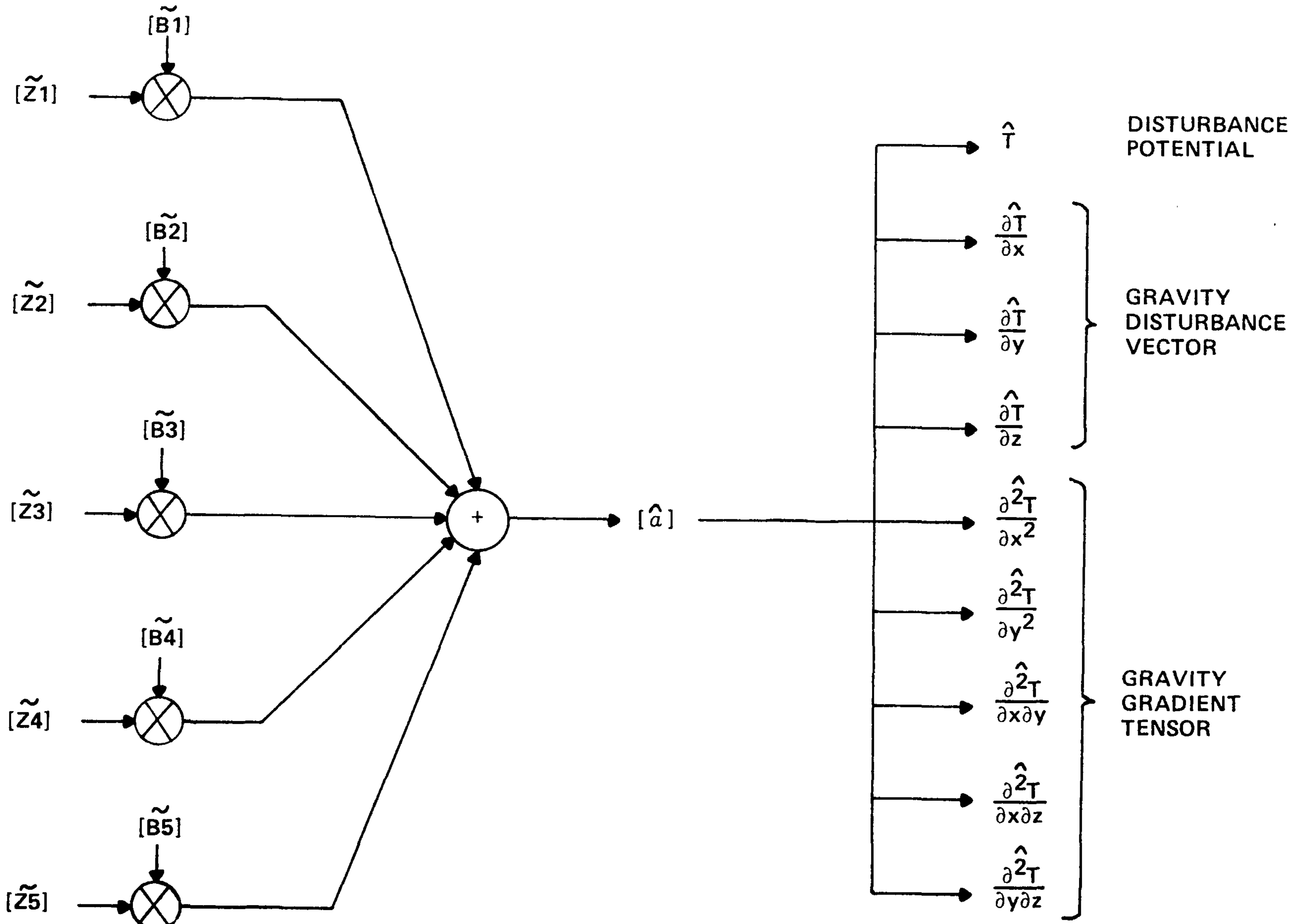
OPTIMAL ESTIMATE OF KARHUNEN-LOEVE COEFFICIENTS



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SUMMARY

- THE MODEL IS DERIVED FROM THE PHYSICAL THEORY OF GEODESY AND IS NOT BASED UPON EMPIRICAL ASSUMPTIONS OF CORRELATION FUNCTIONS OR POWER SPECTRAL DENSITIES
- MODEL CAN ACCOMMODATE MULTIPLE TWO-DIMENSIONAL WHITE NOISE LAYERS BELOW THE SURFACE OF THE EARTH
- EACH LAYER CAN MODEL THE VERTICAL DERIVATIVE OF THE DISTURBANCE POTENTIAL TO ANY ORDER
- NON-ZERO BOUNDARY VALUES FOR THE DISTURBANCE POTENTIAL ON THE EXTERIOR OF THE SURVEY REGION PERMITTED
- THE MODEL IS SUCH THAT AT ANY GIVEN SPATIAL POINT THE GRAVITY FIELD'S CORRELATION WITH NEIGHBORING POINTS IS PRESERVED AND CORRELATION IN ANY DIRECTION IS NOT IGNORED
- THE ESTIMATION ALGORITHM DOES NOT ENFORCE ANY UNNECESSARY LIMITATION OF CAUSALITY ON THE DATA INASMUCH AS NO ONE-DIMENSIONAL SCANNING IS PERFORMED
- EACH COEFFICIENT IN THE SERIES EXPANSION FOR THE GRAVITY FIELD IS ESTIMATED USING ALL THE MULTI-SENSOR DATA SIMULTANEOUSLY
- THE ESTIMATION ALGORITHM CAN HANDLE MULTISENSOR DATA GIVEN IN TWO-DIMENSIONAL GRIDS AT THE SAME OR DIFFERENT ALTITUDES ON OR ABOVE THE SURFACE OF THE EARTH
- DOWNWARD CONTINUATION OF THE GRAVITY FIELD FROM MEASUREMENTS ABOVE THE SURFACE OF THE EARTH IS AUTOMATICALLY DONE WITHOUT ANY LOSS OF ACCURACY
- INTERPOLATION OF ESTIMATES BETWEEN GRID MEASUREMENTS PERFORMED AUTOMATICALLY
- DIFFERENT APRIORI ACCURACIES CAN BE ASSIGNED TO MEASUREMENTS FROM DIFFERENT SENSORS
- CORRELATED NOISE SOURCES CAN BE ACCOMMODATED TO THE EXTENT THAT THEY CAN BE REPRESENTED BY THE BASIS FUNCTIONS
- ESTIMATION ALGORITHM REQUIRES NO MATRIX INVERSIONS
- MEASUREMENT DATA MUST BE IN PLANAR GRIDDED FORM

STUDY OF THE HIGH FREQUENCY SPECTRUM OF ANOMALOUS POTENTIAL

A.A. Vassiliou and K.P. Schwarz

Objectives

1. High frequency gravity spectrum knowledge necessary for airborne gradiometry survey design and data processing techniques.

2. Gravity models needed for real-time and post-mission processing techniques of gradiometer data.

Data available

1. High frequency spectrum from dense gravity anomalies.

2. Degree variance models from $(5' \times 5')$ or $(5' \times 10')$ gravity anomalies.

2 Applications of FFT for gridded 2-D data

- Direct DFT (stationarity assumed)

$$G(m,n) = F\{g(k,\ell)\} = \frac{T_x}{M}\,\frac{T_y}{N}\sum_{k=0}^{M-1}\sum_{\ell=0}^{N-1} g(k,\ell)\,e^{-j2\pi\left(\frac{mk}{M}+\frac{n\ell}{N}\right)}$$

- Inverse DFT

$$g(k,\ell) = F^{-1}\{G(m,n)\} = \frac{1}{T_x}\,\frac{1}{T_y}\sum_{m=0}^{M-1}\sum_{\ell=0}^{N-1} G(m,n)\,e^{j2\pi\left(\frac{mk}{M}+\frac{n\ell}{N}\right)}$$

- Unbiased estimate of PSD function given a number of ν sample records

$$\hat{S}_{gg}(m,n) = \frac{1}{\nu T_x T_y}\sum_{T=1}^{\nu} H_T^{*}(m,n)\,H_T(m,n)$$

- Covariance function

$$\hat{C}_{gg}(k,\ell) = F^{-1}\{\hat{S}_{gg}(m,n) - \hat{S}_{gg}(0,0)\,\delta(m,n)\}$$

- Assuming isotropic gravity field the spherical degree variances
  - anomalous potential $\sigma_\ell^2 = \frac{1}{2\pi}\,\frac{\ell+\frac{1}{2}}{\ell^2}\,S_{gg}\left(\frac{\ell+\frac{1}{2}}{R}\right)$
  - gravity anomaly $c_\ell^2 = \frac{1}{2\pi}\,\frac{\ell+\frac{1}{2}}{R^2}\,S_{gg}\left(\frac{\ell+\frac{1}{2}}{R}\right)$

- The computed 2-D PSD is averaged over all azimuths to yield an isotropic PSD

- Reduced spectral leakage - windowing
  Correcting factor

3. Results from dense gravity data samples

- Four non-mountainous sample areas

Area	Number of grav. anomalies	Area size North x East (Km^2)	variance ($mgals^2$)
1	3512	40 × 80 = 3200	28
2	8715	60 × 150 = 9000	176
3	4796	70 × 70 = 4900	56
4	5214	70 × 70 = 4900	92

- Flat earth approximation used

$$\left. \begin{array}{l} dx = R\cos\phi \, d\lambda \\ dy = R d\phi \end{array} \right\}$$

- Point gravity anomalies gridded on 1×1 km grid, windowed, processed by FFT.

- PSD computed – power distribution with frequency.

- 1 mgal detectable at 5-6 km wavelengths, or 3 km grid spacing - Nyquist frequency.

- 3 km grid spacing alternative track spacing for airborne gradiometry survey.

- Covariance functions of Δg – not isotropic in many cases

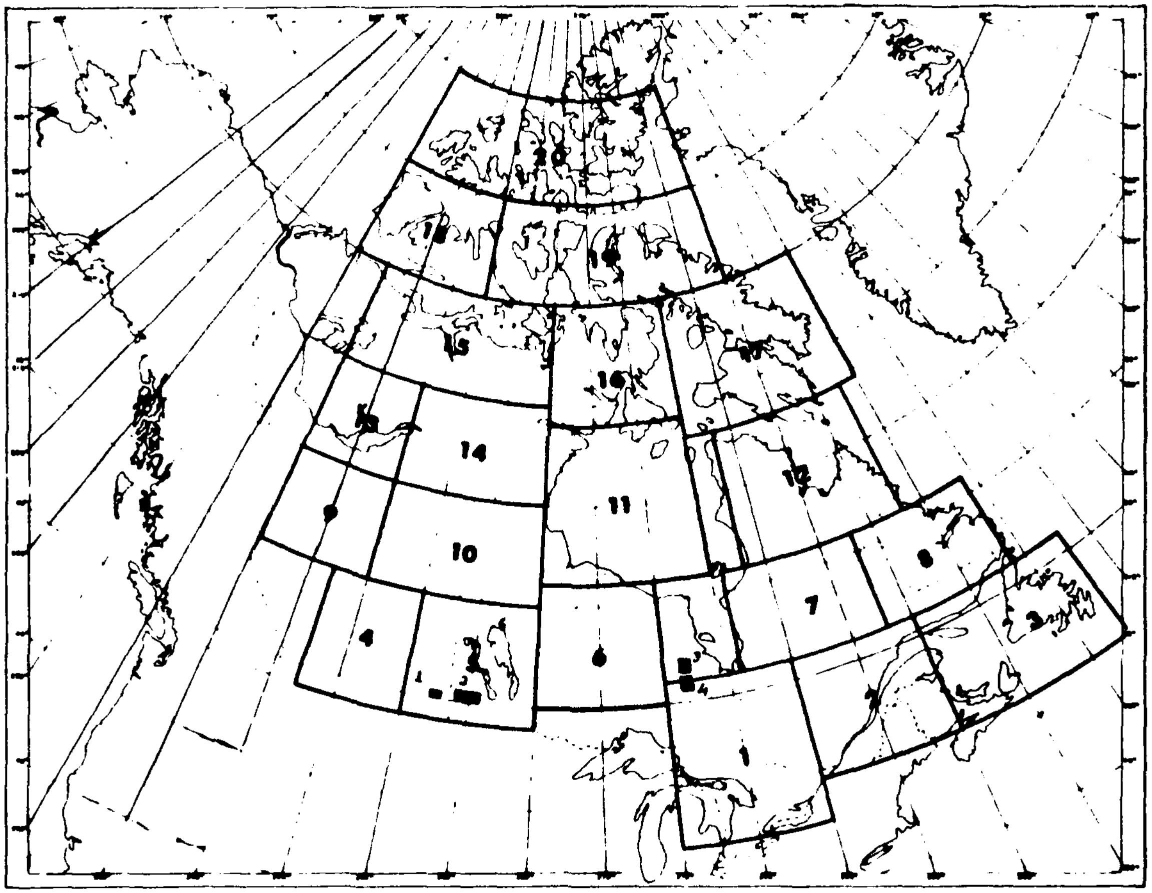

Figure 1 : Distribution of sample areas

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4. Results from mean 5'x5' gravity anomalies

- Mean gravity anomalies referenced to GEM10B.
  A 5° equal area block selected as minimum area size.

- 16 sample areas in non-mountainous Canada territory.

- Same flat earth approximation used as before.

- PSD and covariance functions computed

- Isotropic PSD by averaging over all azimuths
  Degree variances for all 16 sample areas from isotropic PSD

- Gravity anomaly degree variances modelled

$$c_\ell^2 = \frac{A}{\ell^{x_g}}$$

- Straight line fit for determining A, x_g

$$2\ln c_\ell = \ln A - x_g \ln \ell$$

- Results of straight line fit from 16 sample areas

$$x_g = 1.6 \pm 0.13$$

- Anomalous potential degree variances modelled

$$\sigma_\ell^2 = \frac{B}{\ell^{3.6}}$$

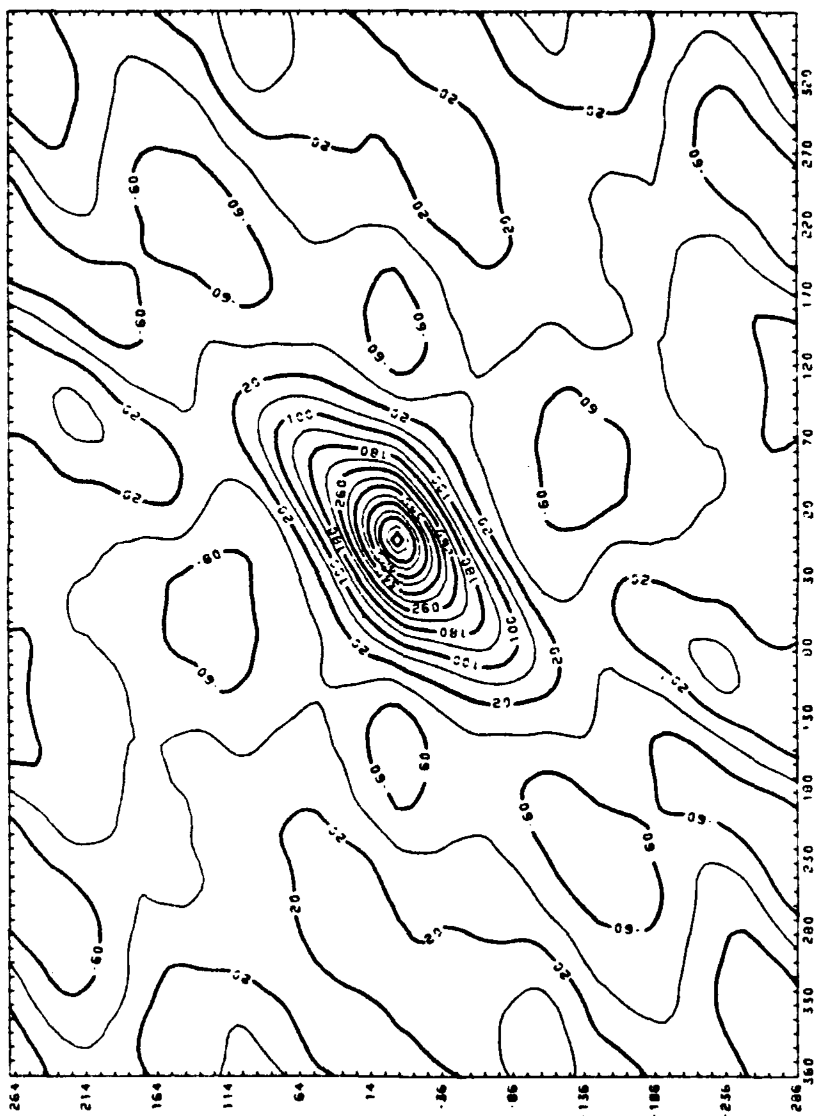

Figure 7 : Covariance function of gravity anomaly
for sample area 2

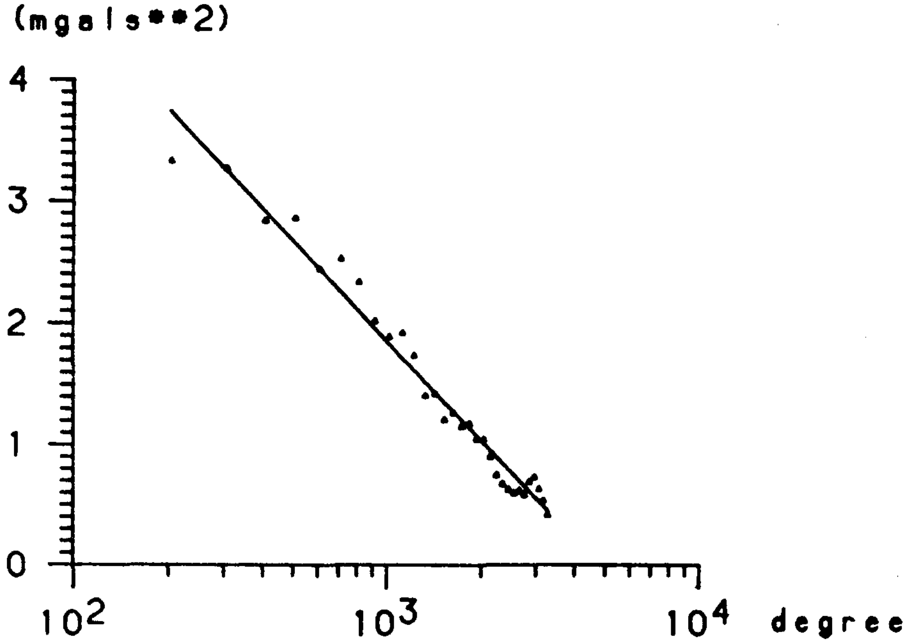

Figure 10 : Straight line fit for the gravity anomaly degree variances for the sample area 1

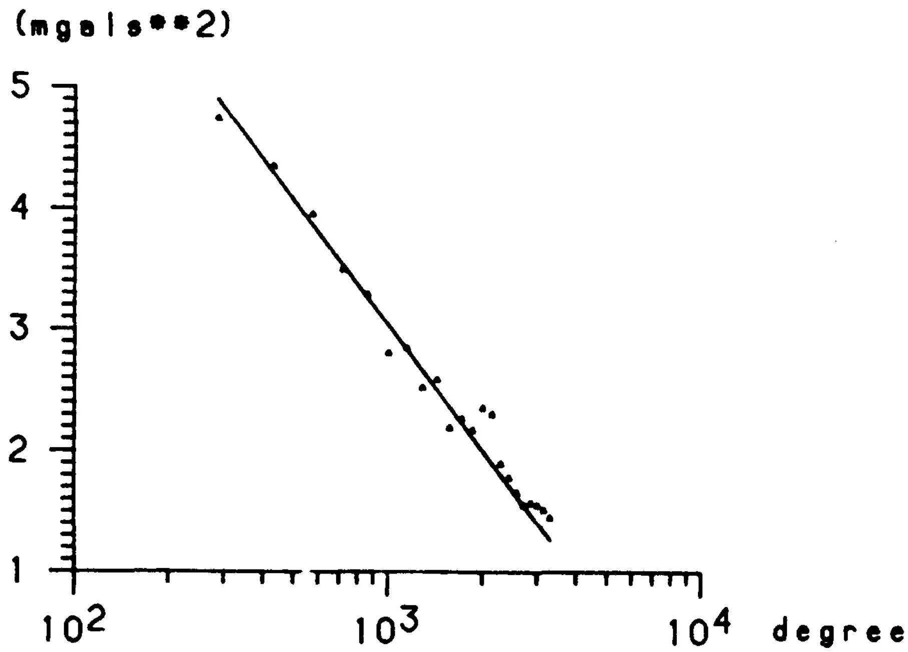

Figure 11 : Straight line fit for the gravity anomaly degree variances for the sample area 2

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5. Implications for the modelling of the anomalous potential covariance function

- The gravity anomaly degree variance model

$$c_\ell^2 = \frac{A}{\ell^{2.6}}$$

implies that the gravity anomaly PSD decay like

$$S_{gg}(\omega) \sim \omega^{-2.6} \qquad \text{or} \quad S_{gg}(\omega) = \frac{E_1}{\omega^{2.6}}$$

- Since $S_{TT}(\omega)$ can be expressed in terms of $S_{gg}(\omega)$

$$S_{TT}(\omega) = \frac{S_{gg}(\omega)}{\omega^2}$$

the anomalous potential PSD is modelled

$$S_{TT}(\omega) = \frac{D_1}{\omega^{4.6}}$$

- Several covariance models proposed in the past. Among them, third-order Gauss-Markov, Tscherning-Rapp, second-order Gauss Markov for Δg, reciprocal distance.

- If a third-order Gauss-Markov covariance model used

$$C_{TT}(r) = \sigma_T^2\left(1+\beta r+\frac{1}{3}\beta^2 r^2\right)e^{-\beta r}$$

high degree variances contain too little power

- If a second-order Gauss-Markov Δg covariance model used

$$C_{T_rT_r}(r) = \sigma_g^2(1+\beta r)e^{-\beta r}$$

high degree variances contain too little power

- If a repicrocal distance covariance model used

$$C_{TT}(r) = \frac{\sigma_T^2}{(1+\alpha^2 r^2)^{1/2}}$$

high degree variances contain too much power

- Degree variance model from actual data do not behave like Kaula's rule or Rapp-Tscherning model

- Covariance models used (assumed $z=0$)

1. Third-order Gauss-Markov for T.
2. Second-order Gauss-Markov for Δg.
3. Reciprocal distance for T.
4. Tscherning-Rapp*.
5. Second-order Gauss-Markov for T.

Covariance models

PSD	1	2	3	4	5	Actual data models
$S_{TT}(\omega)$	$\sim \omega^{-7}$	$\sim \omega^{-7}$	$\sim \frac{e^{-\omega a}}{\omega a}$	$\sim \omega^{-4}$	$\sim \omega^{-5}$	$\sim \omega^{-4.6}$
$S_{T_rT_r}(\omega)$	$\sim \omega^{-5}$	$\sim \omega^{-5}$	$\sim \frac{\omega e^{-\omega a}}{a}$	$\sim \omega^{-2}$	$\sim \omega^{-3}$	$\sim \omega^{-2.6}$

* Depends on the depth of the Bjerhammar sphere

- The gravity data agree well with a second-order Gauss Markov anomalous potential covariance model

$$T \quad \begin{cases} C_{TT}(r) = \sigma_T^2 (1+\beta r) e^{-\beta r} \\ S_{TT}(\omega) = 6\pi \sigma_T^2 \beta^3 \dfrac{1}{(\beta^2+\omega^2)^{5/2}} \end{cases}$$

$$\delta g \quad \begin{cases} C_{T_r T_r}(r) = 2\sigma_T^2 \beta^2 \left(1 - \dfrac{\beta}{2} r\right) e^{-\beta r} \\ S_{T_r T_r}(\omega) = 6\pi \sigma_T^2 \beta^3 \dfrac{\omega^2}{(\beta^2+\omega^2)^{5/2}} \end{cases}$$

$$T_{rr} \quad \begin{cases} C_{T_{rr} T_{rr}}(r) = 3\sigma_T^2 \beta^3 \left(\dfrac{1}{r} - \beta\right) e^{-\beta r} \\ S_{T_{rr} T_{rr}}(\omega) = 6\pi \sigma_T^2 \beta^3 \dfrac{\omega^4}{(\omega^2+\beta^2)^{5/2}} \end{cases}$$

- Drawbacks of this second-order Gauss-Markov model
  - There are no analytical expressions for its upward continuation in the spatial domain
  - The $C_{T_r T_r}(r)$ is not rounded at $r=0$
  - This covariance model has infinite gradient variance

- Two last drawbacks can be eliminated by just slightly modifying the $C_{T_r T_r}(r)$, $C_{T_{rr} T_{rr}}(r)$ models, loosing the model self-consistency.
  Furthermore, the upward continuation drawback can be overcome is the data processing is done in the frequency domain.

Conclusions

- To get a gravity disturbance resolution to 1 mgal, a 3 Km grid spacing can be considered as giving an effective Nyquist frequency

- Results from mean (5'x5') gravity anomalies indicate that the high degree variances of the anomalous potential decay like $\ell^{-2.6}$, and not like ℓ^{-3} as the models by Kaula or Tscherning-Rapp imply.

- The third-order Gauss-Markov, the reciprocal distance as anomalous potential covariance models as well as the second-order Gauss-Markov gravity anomaly model do not fit the gravity data.

- A second-order Gauss-Markov model agrees well with the data but has some theoretical drawbacks.

- No degree variance models were obtained for mountainous areas of Canada, due to insufficient data sets. This analysis will be made as soon as good gravity coverage will be available.

BASIC CONCEPTS IN REAL-TIME PROCESSING OF GRAVITY GRADIOMETER DATA

PRESENTED AT
13TH MOVING BASE GRAVITY GRADIOMETER CONFERENCE
UNITED STATES AIR FORCE ACADEMY

12-13 FEBRUARY 1985

PRESENTED BY

WILLIAM CHAIRETAKIS
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SYSTEMS MANAGEMENT GROUP
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CONTENTS

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PART I: INTRODUCTION

- THE RESULTS TO BE PRESENTED APPLY TO A MOVING BASE GRADIOMETER SYSTEM CONSISTING OF THREE CAROUSELLED GRAVITY GRADIOMETER INSTRUMENTS (BELL GGIs) IN AN UMBRELLA CONFIGURATION

- IN PREVIOUS YEARS, PRESENTATIONS HAVE BEEN GIVEN BY

    - BELL, ON THE GRAVITY GRADIOMETER INSTRUMENT (GGI) THEORY OF OPERATION

    - SPERRY, ON THE USE OF LOCAL LEVEL GRADIENTS TO ESTIMATE (IN REAL TIME) VERTICAL DEFLECTION AND OTHER GRAVITATIONAL ANOMALIES

- THIS PRESENTATION DESCRIBES REAL-TIME TECHNIQUES, USING ONLY GRADIOMETER DATA, TO:

    - OBTAIN ESTIMATES OF THE LOCAL LEVEL GRADIENTS FROM TWO OR THREE INSTRUMENTS

    - ELIMINATE THE EFFECTS OF LOW FREQUENCY INSTRUMENT ERRORS FROM THE GRADIENTS

    - FILTER OUT EXCESSIVE HIGH FREQUENCY INSTRUMENT ERRORS AND MONITOR INSTRUMENT PERFORMANCE

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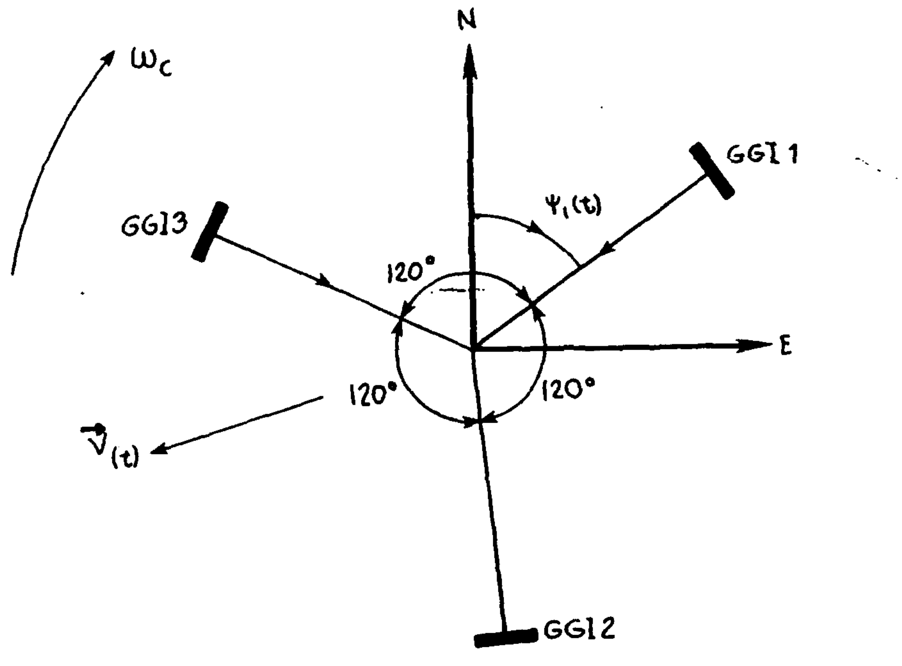
PART II: SYSTEM DESCRIPTION

- THE AXES OF THE THREE GGIs FORM AN ORTHOGONAL COORDINATE SYSTEM WHOSE SYMMETRY AXIS IS KEPT VERTICAL (UMBRELLA CONFIGURATION). THE SYSTEM IS ROTATED CONTINUOUSLY AROUND THIS AXIS AT CONSTANT RATE (CAROUSELLING). IN A LOCAL NORTH, EAST, DOWN (NED) COORDINATE SYSTEM THAT IS ATTACHED TO A RANDOMLY MOVING BASE AND KEPT PARALLEL TO A REFERENCE EARTH-ELLIPSOID, THE CONFIGURATION IS



$$\omega_c = 2\pi / T_c$$

T_c : CAROUSEL PERIOD

$$\psi(t) = \omega_c t$$

$$\psi_1(t) = \psi(t)$$

$$\psi_2(t) = \psi(t) + 120^\circ$$

$$\psi_3(t) = \psi(t) + 240^\circ$$

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SYSTEM DESCRIPTION (CONT)

- EACH GGI HAS TWO OUTPUTS: PRINCIPAL OR INCLINE ($P_i(t), i = 1,2,3$) AND CROSS ($X_i(t), i = 1,2,3$). THEY REPRESENT THE LOCAL LEVEL GRADIENT TENSOR

$$\left[\Gamma_{NED}(t)\right] = \begin{bmatrix} \Gamma_{NN}(t) & \Gamma_{NE}(t) & \Gamma_{ND}(t) \\ \Gamma_{NE}(t) & \Gamma_{EE}(t) & \Gamma_{ED}(t) \\ \Gamma_{ND}(t) & \Gamma_{ED}(t) & \Gamma_{DD}(t) \end{bmatrix}$$

$$\Gamma_{NN}(t) + \Gamma_{EE}(t) + \Gamma_{DD}(t) = \text{CONSTANT} \qquad \text{(POISSON EQUATION)}$$

AS

$$P_i(t) = \underset{\sim}{M}^T(\psi_i(t)) \; \underset{\sim}{S}_P(t)$$

$$X_i(t) = \underset{\sim}{M}^T(\psi_i(t)) \; \underset{\sim}{S}_X(t)$$

$$\psi_i(t) = \psi(t) + \frac{2\pi}{3}(i-1)$$

$i = 1,2,3$ LABELS THE GGIs

SYSTEM DESCRIPTION (CONT)

$$\underset{\sim}{S}_p(t) = \begin{bmatrix} 0 \\ -\sqrt{\frac{2}{3}}\,\Gamma_{ND}(t) \\ \sqrt{\frac{2}{3}}\,\Gamma_{ED}(t) \\ -\frac{1}{2\sqrt{3}}\left(\Gamma_{NN}(t)-\Gamma_{EE}(t)\right) \\ \frac{1}{\sqrt{3}}\,\Gamma_{NE}(t) \end{bmatrix} \qquad \underset{\sim}{S}_x(t) = \begin{bmatrix} \frac{1}{2}\,\Gamma_{DD}(t) \\ \frac{\sqrt{2}}{3}\,\Gamma_{ED}(t) \\ \frac{\sqrt{2}}{3}\,\Gamma_{ND}(t) \\ \frac{2}{3}\,\Gamma_{NE}(t) \\ \frac{1}{3}\left(\Gamma_{NN}(t)-\Gamma_{EE}(t)\right) \end{bmatrix} \qquad \underset{\sim}{M}(\psi_i) = \begin{bmatrix} 1 \\ \sin\psi_i \\ \cos\psi_i \\ \sin 2\psi_i \\ \cos 2\psi_i \end{bmatrix}$$

NOTE THAT

$$\sum_{i=1}^{3} \underset{\sim}{M}(\psi_i) = 3\,\underset{\sim}{u} \quad , \quad \underset{\sim}{u} \equiv \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

AND THE CONSTRAINTS

$$\sum_{i=1}^{3} P_i(t) = 0$$

$$\sum_{i=1}^{3} X_i(t) = \frac{3}{2}\,\Gamma_{DD}(t)$$

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SYSTEM DESCRIPTION (CONT)

- GGI PURE INSTRUMENT ERRORS ARE MODELED IN THE STEADY STATE MEASUREMENTS BY

$$\hat{\Gamma}_i(t) = \Gamma_i(t) + \delta\Gamma_i(t) \qquad \hat{X}_i(t) = X_i(t) + \delta X_i(t)$$

$$\delta\Gamma_i(t) = B_{\Gamma i} + R_{\Gamma i}\,t + n_{\Gamma i}(t) \qquad \delta X_i(t) = B_{xi} + R_{xi}\,t + n_{xi}(t)$$

WHERE

$\{B_{\Gamma i}, B_{xi}\}$ = BIASES (RANDOM)

$\{R_{\Gamma i}, R_{xi}\}$ = RAMPS (RANDOM

$\{n_{\Gamma i}(t), n_{xi}(t)\}$ = RANDOM INSTRUMENT NOISE (PLUS ANY REMAINING UNCOMPENSATED ERROR, E.G. BASE MOTION SENSITIVITY ETC.)

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SYSTEM DESCRIPTION (CONT)

- THE SPECTRAL CONTENT OF THE NOISE $n(t)$ CAN BE TAKEN TO BE WHITE AT HIGH FREQUENCIES X X X . AT LOW FREQUENCIES, INSTRUMENT INSTABILITES/DRIFT TYPICALLY INCREASE THIS BY TWO ORDERS OF MAGNITUDE

PART III: THREE-GGI GRADIENT COMPUTATION

- THE $\{P_i, X_i \,;\, i=1,2,3\} \longrightarrow [\Gamma_{NED}]$ TRANSFORMATION IS NEITHER STRAIGHTFORWARD NOR UNIQUE: TO OBTAIN UNIQUENESS AN ADDITIONAL CONSTRAINT IS REQUIRED. OVERALL SYSTEM SYMMETRY DICTATES THE IMPOSITION OF THE FOLLOWING CONSTRAINT:

  o THE NED GRADIENTS OBTAINED FROM THE GRADIOMETER SHOULD BE INVARIANT UNDER ALL PERMUTATIONS OF THE THREE INSTRUMENTS.

- THE TRANSFORMATION IS

$$\underset{\sim}{\Gamma}_{NED}(t) = \underset{\sim}{G}(t)\, \underset{\sim}{M}(\psi(t))$$

WHERE

$$\underset{\sim}{\Gamma}_{NED}(t) = \begin{bmatrix} \Gamma_{NN}(t) \\ \Gamma_{EE}(t) \\ \Gamma_{NE}(t) \\ \Gamma_{ND}(t) \\ \Gamma_{ED}(t) \end{bmatrix} \qquad \underset{\sim}{G}(t) = \begin{bmatrix} -X(t) & 0 & 0 & U_2(t) & V_2(t) \\ -X(t) & 0 & 0 & -U_2(t) & -V_2(t) \\ 0 & 0 & 0 & V_2(t) & -U_2(t) \\ 0 & U_1(t) & V_1(t) & 0 & 0 \\ 0 & V_1(t) & -U_1(t) & 0 & 0 \end{bmatrix}$$

THREE-GGI GRADIENT COMPUTATION (CONT)

WITH THE DEFINITIONS

$$X(t) = \frac{1}{3} \sum_{i=1}^{3} X_i(t) = \frac{1}{2} \Gamma_{DD}(t)$$

$$U_1(t) = \frac{\sqrt{2}}{3\sqrt{3}} \left[I_{31}(t,0) - I_{12}(t,0) \right] - \frac{1}{\sqrt{6}} C_{23}(t,0)$$

$$U_2(t) = \frac{1}{3\sqrt{3}} \left[I_{31}(t,0) - I_{12}(t,0) \right] + \frac{1}{\sqrt{3}} C_{23}(t,0)$$

$$V_1(t) = \frac{1}{3\sqrt{2}} \left[C_{12}(t,0) - C_{31}(t,0) \right] - \frac{\sqrt{2}}{3} I_{23}(t,0)$$

$$V_2(t) = \frac{1}{3} \left[C_{12}(t,0) - C_{31}(t,0) \right] + \frac{1}{3} I_{23}(t,0)$$

$$I_{ij}(t,0) = P_i(t) - P_j(t)$$

$$C_{ij}(t,0) = X_i(t) - X_j(t)$$

THREE-GGI GRADIENT COMPUTATION (CONT)

- IF THE MEASUREMENTS $\{\hat{P}_i(t), \hat{X}_i(t); i = 1, 2, 3\}$ UNDERGO THIS TRANSFORMATION THE FOLLOWING GRADIENT ERRORS RESULT

$$\delta \underset{\sim}{\Gamma}_{NED}(t) = [\delta \underset{\sim}{G}(t)]\, \underset{\sim}{M}(\psi_i(t))$$

$$\delta \underset{\sim}{\Gamma}_{NED}(t) = \begin{bmatrix} \delta\Gamma_{NN}(t) \\ \delta\Gamma_{EE}(t) \\ \delta\Gamma_{NE}(t) \\ \delta\Gamma_{ND}(t) \\ \delta\Gamma_{ED}(t) \end{bmatrix} \quad \text{AND} \quad \delta \underset{\sim}{G}(t) = \begin{bmatrix} -\delta X(t) & 0 & 0 & \delta U_2(t) & \delta V_2(t) \\ -\delta X(t) & 0 & 0 & -\delta U_2(t) & -\delta V_2(t) \\ 0 & 0 & 0 & \delta V_2(t) & -\delta U_2(t) \\ 0 & \delta U_1(t) & \delta V_1(t) & 0 & 0 \\ 0 & \delta V_1(t) & -\delta U_1(t) & 0 & 0 \end{bmatrix}$$

$$\delta X(t) = \frac{1}{3}\sum_{i=1}^{3} \delta X_i(t)$$

$$\delta U_1(t) = \frac{\sqrt{2}}{3\sqrt{3}}\left[\delta I_{31}(t,0) - \delta I_{12}(t,0)\right] - \frac{1}{\sqrt{6}}\,\delta C_{23}(t,0)$$

$$\delta U_2(t) = \frac{1}{3\sqrt{3}}\left[\delta I_{31}(t,0) - \delta I_{12}(t,0)\right] + \frac{1}{\sqrt{3}}\,\delta C_{23}(t,0)$$

$$\delta V_1(t) = \frac{1}{3\sqrt{2}}\left[\delta C_{12}(t,0) - \delta C_{31}(t,0)\right] - \frac{\sqrt{2}}{3}\,\delta I_{23}(t,0)$$

$$\delta V_2(t) = \frac{1}{3}\left[\delta C_{12}(t,0) - \delta C_{31}(t,0)\right] + \frac{1}{3}\,\delta I_{23}(t,0)$$

THREE-GGI GRADIENT COMPUTATION (CONT)

- EXCEPT FOR $\delta X(t)$, THE ERRORS ARE MODULATED BY THE $\underset{\sim}{M}(\Psi_i)$ FUNCTION.
- THE OSCILLATORY ERRORS ARE (IN TERMS OF INSTRUMENT ERRORS)

$$\delta \Gamma_{ij}(t,o) = B_{Pij} + R_{Pij}t + n_{Pij}(t)$$

$$\delta C_{ij}(t,o) = B_{Xij} + R_{Xij}t + n_{Xij}(t)$$

WHERE

$$B_{Pij} = B_{Pi} - B_{Pj} \qquad B_{Xij} = B_{Xi} - B_{Xj}$$

$$R_{Pij} = R_{Pi} - R_{Pj} \qquad R_{Xij} = R_{Xi} - R_{Xj}$$

$$n_{Pij}(t) = n_{Pi}(t) - n_{Pj}(t) \qquad n_{Xij}(t) = n_{Xi}(t) - n_{Xj}(t)$$

- THE MISMATCHES IN INSTRUMENT BIASES, RAMPS, AND LOW FREQUENCY NOISE WILL CREATE LARGE ERROR OSCILLATIONS IN ALL GRADIENTS:

  o FOR $\delta\Gamma_{NN}, \delta\Gamma_{EE}, \delta\Gamma_{NE}$ CENTERED AROUND $2W_C$
  o FOR $\delta\Gamma_{NO}, \delta\Gamma_{EO}$ CENTERED AROUND $1W_C$

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THREE-GGI GRADIENT COMPUTATION (CONT)

- THE OSCILLATIONS ARE NOT SHARP, BUT HAVE A FINITE SPECTRAL BANDWIDTH
  - o THIS PROPERTY MAKES THEIR REAL-TIME REMOVAL DIFFICULT
- GRAVITY GRADIENT SIGNATURE IN THE SPECTRAL REGION OF THE OSCILLATIONS IS AN ADDITIONAL COMPLICATION

$$\omega_c - m\Delta\omega_{GGI} \lesssim \omega \lesssim \omega_c + m\Delta\omega_{GGI} \qquad (m \sim 2)$$

  - o IT IS DESIRABLE TO REMOVE THE OSCILLATORY ERRORS WITHOUT AFFECTING THIS SIGNATURE
- THESE OBJECTIVES CAN BE ACCOMPLISHED BY
  - o COMPUTATION (IN REAL TIME) OF THE LOW FREQUENCY PORTION OF THE $\delta I_{ij}(t,o)$, $\delta C_{ij}(t,o)$ ERRORS AS DESCRIBED IN PART IV
  - o DIRECT COMPENSATION OF THE MEASUREMENTS

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THREE-GGI GRADIENT COMPUTATION (CONT)

$$\hat{I}_{ij}(t,o) \longrightarrow \hat{I}_{ij}(t,o) - \delta I_{ij}^{LF}(t,o)$$

$$\hat{C}_{ij}(t,o) \longrightarrow \hat{C}_{ij}(t,o) - \delta C_{ij}^{LF}(t,o)$$

BEFORE INSERTION IN THE TRANSFORMATION

- THE UNMODULATED ERROR $\delta X(t)$, CONTAMINATES THE DIAGONAL GRADIENTS AND CANNOT BE ESTIMATED WITHOUT INFORMATION EXTERNAL TO THE SYSTEM (E.G. GRAVITY MODELS OR MAPS). THIS IS A FUNDAMENTAL LIMITATION OF THE SYSTEM DESIGN.
  - o ONE WAY TO MINIMIZE THIS ERROR, SOLELY WITHIN THE CONTEXT OF THE GRADIOMETER SYSTEM, WILL BE PRESENTED IN PART VII.

PART IV: REAL-TIME ERROR ESTIMATION TECHNIQUE

- INTRODUCTION

  - CONSIDER THE LAGGED INSTRUMENT DIFFERENCES

$$I_{ij}(t,\tau) = P_i(t) - P_j(t-\tau)$$

$$C_{ij}(t,\tau) = X_i(t) - X_j(t-\tau)$$

$$\tau \geqslant 0$$

  - INTRODUCE A TIME TRANSLATION OPERATOR $\underset{\sim}{T}$ SUCH THAT

$$\underset{\sim}{M}(t+t') = \underset{\sim}{T}(t)\,\underset{\sim}{M}(t')$$

$$\underset{\sim}{T}(0) = \underset{\sim}{I} \quad (= \text{IDENTITY}) .$$

THIS OPERATOR CONSISTS OF ROTATION SUBMATRICES AND HAS THE PROPERTIES

$$\underset{\sim}{T}^{T}(t) = \underset{\sim}{T}(-t) = \underset{\sim}{T}^{-1}(t) .$$

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REAL-TIME ERROR ESTIMATION TECHNIQUE (CONT)

EXPLICITLY

$$\underset{\sim}{T}(t) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & \cos\omega_c t & \sin\omega_c t & 0 & 0 \\ 0 & -\sin\omega_c t & \cos\omega_c t & 0 & 0 \\ 0 & 0 & 0 & \cos 2\omega_c t & \sin 2\omega_c t \\ 0 & 0 & 0 & -\sin 2\omega_c t & \cos 2\omega_c t \end{bmatrix}$$

o USE THIS TO REWRITE

$$I_{ij}(t,\tau) = \underset{\sim}{M}^T(t)\left\{ \underset{\sim}{T}(\tau-\tau_j)\left[\Delta_\tau \underset{\sim}{S}_p(t)\right] + \underset{\sim}{T}(-\tau_i)\left[\underset{\sim}{I} - \underset{\sim}{T}(\tau+\tau_i-\tau_j)\right]\underset{\sim}{S}_p(t)\right\}$$

$C_{ij}(t,\tau)$ = AS ABOVE WITH $\underset{\sim}{S}_p(t) \rightarrow \underset{\sim}{S}_x(t)$

WHERE $i,j = 1,2,3$ AND

$$\tau_i = \frac{1}{3}(i-1)T_c$$

$$\Delta_\tau \underset{\sim}{S}(t) = \underset{\sim}{S}(t) - \underset{\sim}{S}(t-\tau)$$

- NEXT MINIMIZE THE $I_{ij}(t,\tau)$, $C_{ij}(t,\tau)$ (SIMULTANEOUSLY) WITH RESPECT TO τ

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REAL-TIME ERROR ESTIMATION TECHNIQUE (CONT)

- CLASSICAL MINIMIZATION PROCEDURES RUN INTO DIFFICULTIES SINCE THE RESULT WILL DEPEND ON THE LOCAL GRAVITY SIGNATURE $\underset{\sim}{S}_p(t)$, $\underset{\sim}{S}_x(t)$.

- HOWEVER, $\Delta_\tau \underset{\sim}{S}(t)$ IS THE CHANGE IN SIGNATURE DURING τ AND FOR τ SUFFICIENTLY SMALL

$$\left|\Delta_\tau \underset{\sim}{S}(t)\right| \ll \left|\underset{\sim}{S}(t)\right|$$

AN EFFECTIVE MINIMIZATION PROCEDURE IS

(1) CHOOSE $\tau = \tau_0$ WHERE τ_0 IS THE SMALLEST τ THAT ZEROES THE SECOND TERM IN $I_{ij}(t,\tau)$, $C_{ij}(t,\tau)$

(2) ELIMINATE ANY $\Delta_\tau \underset{\sim}{S}(t)$ CONTRIBUTIONS, IF SIGNIFICANT IN SIZE

REAL-TIME ERROR ESTIMATION TECHNIQUE (CONT)

- o IMPLEMENTATION OF THIS PROCEDURE RESULTS IN

$$\tau_o = \min_{i,j} \{\tau_j - \tau_i\}$$

OR FOR $j = i+1 \pmod 3$

$$\tau_o^{min} = T_c/3$$

SO THAT

$$I_{i,i+1}(t, T_c/3) = \underset{\sim}{M}^T(\psi_i(t)) \left[\Delta_{T_c/3} \underset{\sim}{S}_p(t) \right]$$

$$C_{i,i+1}(t, T_c/3) = \underset{\sim}{M}^T(\psi_i(t)) \left[\Delta_{T_c/3} \underset{\sim}{S}_x(t) \right]$$

- THE OBJECTIVE IS TO ESTIMATE THE ERRORS $\delta I_{ij}^{LF}(t,0)$, $\delta C_{ij}^{LF}(t,0)$

- o FROM THE IDENTITY

$$\delta I_{ij}(t,0) = \delta I_{ij}(t,\tau) - \delta I_{jj}(t,\tau)$$

FOLLOWS

$$\delta I_{ij}(t,0) = \hat{I}_{ij}(t,\tau) - I_{ij}(t,\tau) - \delta I_{jj}(t,\tau)$$

AND SIMILARLY FOR $\delta C_{ij}(t,0)$

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REAL-TIME ERROR ESTIMATION TECHNIQUE (CONT)

THE RATIONALE BEHIND THE MINIMIZATION PROCEDURE OF ABOVE WAS TO MINIMIZE/ELIMINATE THE SECOND TERM IN THIS EXPRESSION

- FOR $\tau = T_c/3$ AND $j = i+1 \pmod 3$ $(i = 1, 2, 3)$

$$\delta I_{i,i+1}(t,0) = \hat{I}_{i,i+1}(t, T_c/3) - \underset{\sim}{M}^T(\psi_i(t))\left[\Delta_{T_c/3}\, \underset{\sim}{S}_P(t)\right] - \left[\Delta_{T_c/3}\, \delta P_{i+1}(t)\right]$$

$$\delta C_{i,i+1}(t,0) = \hat{C}_{i,i+1}(t, T_c/3) - \underset{\sim}{M}^T(\psi_i(t))\left[\Delta_{T_c/3}\, \underset{\sim}{S}_X(t)\right] - \left[\Delta_{T_c/3}\, \delta X_{i+1}(t)\right]$$

WHERE

$$\left[\Delta_{T_c/3}\, \delta P_{i+1}(t)\right] = \delta P_{i+1}(t) - \delta P_{i+1}(t - T_c/3)$$

$$\left[\Delta_{T_c/3}\, \delta X_{i+1}(t)\right] = \delta X_{i+1}(t) - \delta X_{i+1}(t - T_c/3)$$

- IT IS OBSERVED THAT

(1) THE FIRST TERM ON THE RIGHT IS AN AVAILABLE REAL-TIME MEASUREMENT

(2) THE SECOND TERM ON THE RIGHT CONTAINS THE CHANGE IN THE ACTUAL EARTH SIGNATURE OVER $T_c/3$ AND MODULATED BY HARMONICS OF W_c

(3) THE THIRD TERM IS THE VERY HIGH ($\omega \gg 3\omega_c$) PORTION OF THE INSTRUMENT WHITE NOISE

REAL-TIME ERROR ESTIMATION TECHNIQUE (CONT)

- THUS, THE LAST TWO TERMS IN THE ABOVE ERROR EXPRESSIONS ARE:

  (1) IN GENERAL, VERY SMALL COMPARED TO THE FIRST TERM AND REPRESENT SECOND ORDER ERROR EFFECTS

  (2) SPECTRALLY WELL SEPARATED FROM THE LOW FREQUENCY PORTION OF THE ERRORS

- THE DESIRED ERROR ESTIMATE IS THEN

$$\delta I^{LF}_{i,i+1}(t,0) = \overline{\hat{I}_{i,i+1}(t, T_c/3)}$$

$$\delta C^{LF}_{i,i+1}(t,0) = \overline{\hat{C}_{i,i+1}(t, T_c/3)}$$

WHERE THE BAR DENOTES A LOW-PASS FILTERING OPERATION

PART V: FURTHER REAL-TIME USAGE OF THE ERROR ESTIMATES

- THE QUANTITIES ESTIMATED ABOVE MAY BE WRITTEN AS

$$\overline{\hat{I}_{i,i+1}(t, T_c/3)} = B_{P_{i,i+1}} + R_{P_{i,i+1}} t + n^{LF}_{P_{i,i+1}}(t)$$

$$n^{LF}_{P_{i,i+1}}(t) = n^{LF}_{P_i}(t) - n^{LF}_{P_{i+1}}(t)$$

AND SIMILARLY FOR THE CROSS COMPONENTS

- THESE MEASUREMENTS CAN BE USED TO MONITOR THE LOW FREQUENCY INSTRUMENT PERFORMANCE IN REAL TIME

  o THE ERRORS OVER A SUFFICIENTLY LONG WINDOW CAN BE LEAST-SQUARES FITTED TO THE ABOVE MODEL TO OBTAIN RUNNING ESTIMATES OF THE DIFFERENCES IN INSTRUMENT NOISE. FROM THE VARIANCES $\sigma^2(n_{P_{ij}})$ OF THIS NOISE, ONE COMPUTES INDIVIDUAL INSTRUMENT ERROR VARIANCES BY

$$\sigma^2_{P_i} = \frac{1}{2} \sum_{j=1}^{3} (-1)^{j-1} \sigma^2(n_{P_{i+j-1,\,i+j}})$$

  (SIMILARLY FOR THE CROSS COMPONENTS)

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FURTHER REAL-TIME USAGE OF THE ERROR ESTIMATES (CONT)

- o THE ABOVE VARIANCE EXPRESSION ASSUMES THAT THE INSTRUMENTS LOW FREQUENCY NOISE ARE UNCORRELATED. FOR PURPOSES OF REAL-TIME PERFORMANCE MONITORING THESE ESTIMATES ARE SUFFICIENT

- o IMPLEMENTATION OF MORE SOPHISTICATED MODELING FOR ENVIRONMENTAL SENSITIVITIES IS NOT PRECLUDED

- THE UNFILTERED ERROR DIFFERENCES OF PART IV CAN BE USED TO DESIGN AN EDITOR FILTER THAT DETECTS EXCESSIVE INSTRUMENT ERRORS AND EDITS THE DATA ACCORDINGLY

  - o NEGLECTING THE $\Delta_{\tau_c/3} S(t)$ TERM,

$$\hat{I}_{i,i+1}(t, \tau_c/3) \simeq B_{p i,i+1} + R_{p i,i+1} t + [n_i(t) - n_{p i+1}(t - \tau_c/3)]$$

THE MEASUREMENT ON THE LEFT REPRESENTS PURE INSTRUMENT ERROR AND HAS WELL KNOWN STATISTICAL PROPERTIES (FROM EXISTING ERROR MODELS, TEST RUNS, ETC.)

  - o A REAL-TIME EDITOR FILTER BASED ON THESE PROPERTIES IS CAPABLE (IN ITS STEADY STATE) OF DETECTING AND BOUNDING EXCESSIVE NOISE $n_i(t)$ IN THE $\hat{R}_i(t)$ OUTPUT. SIMILARLY WITH THE CROSS OUTPUT $X_i(t)$

FURTHER REAL-TIME USAGE OF THE ERROR ESTIMATES (CONT)

- IT HAS BEEN ASSUMED THAT THE SIGNATURE TERM

$$\underset{\sim}{M}^T(\psi_i(t))\,\Delta_{\tau_c/2}\,\underset{\sim}{S}(t)$$

IS NEGLIGIBLE. THERE ARE CIRCUMSTANCES WHERE THIS TERM IS SIZABLE

o THE AMPLITUDE OF THE OSCILLATIONS DEPENDS ON

(1) THE RATIO OF THE MOVING BASE SPEED TO THE CAROUSEL RATE

(2) THE AMOUNT OF ANOMALOUS GRAVITY ACTIVITY IN THE OPERATING AREA

FOR A CAROUSEL RATE OF 500°/HR AND A SHIPBORNE GRADIOMETER, EXTREME VALUES OF X X ARE POSSIBLE (E.G. SHIP MANEUVERS, AT X KNOTS, OVER THE BLAKE ESCARPMENT)

o THE SPECTRAL CONTENT OF THE TERM IS CONFINED TO THE BANDWIDTH

$$\omega_c \lessapprox \omega \lessapprox 5\omega_c$$

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FURTHER REAL-TIME USAGE OF THE ERROR ESTIMATES (CONT)

IF THIS REGION IS OF IMPORTANCE (AS IN THE EDITOR FILTER) THE TERM CAN NOT BE FILTERED OUT

- IT IS DESIRABLE TO ELIMINATE THIS SECOND ORDER ERROR TERM DIRECTLY

  - AFTER THE PROCESSING, THE GRADIOMETER PROVIDES NED-GRADIENTS, CLEAN IN THE FREQUENCY RANGE OF THE SIGNATURE ERROR TERM. HIGHER FREQUENCY NOISE IN THE GRADIENTS CAN BE SMOOTHED OUT

  - THE NED-GRADIENT OUTPUT IS THEN FED BACK (IN REAL-TIME) INTO THE PROCESSING FOR COMPUTATION OF THE SIGNATURE TERM AND SUBSEQUENT DIRECT COMPENSATION OF THE ERROR DIFFERENCE MEASUREMENTS

  - THIS INTRODUCES A SMALL AMOUNT OF HIGH FREQUENCY WHITE NOISE INTO THE ERROR ESTIMATES $\delta I_{i,i+1}(t,o)$, $\delta C_{i,i+1}(t,o)$. THIS NOISE HAS BEEN BOUNDED BY THE EDITOR AND IS FURTHER ATTENUATED BY THE FILTERING OPERATION (PART IV).

PART VI: SINGLE-PAIR GRADIENTS TECHNIQUE

- THE NED GRADIENT COMPUTATION DESCRIBED REQUIRES INPUT FROM THREE GGIs. A TECHNIQUE IS NOW PRESENTED THAT ALLOWS FOR THE "INSTANTANEOUS" COMPUTATION (IN REAL-TIME) OF THE NED GRADIENTS FROM THE INPUT OF ONLY TWO GGIs. THE TECHNIQUE IS ILLUSTRATED IN THE SIMPLEST POSSIBLE CASE, THAT OF THE ERROR-FREE GGIs.

- CONSIDER AN ERROR-FREE GRADIOMETER WITH THE j^{th} GGI $(j=1,2,3)$ MISSING. THE INSTANTANEOUS OUTPUTS OF THE MISSING INSTRUMENT CAN BE SIMULATED AND THE SAME THREE-GGI REAL-TIME ALGORITHMS OF PARTS III, IV, V CAN BE IMPLEMENTED.

  - THE SIMULATION USES THE GRADIOMETER CONSTRAINTS OF PART II, TO SET THE OUTPUTS OF THE MISSING (j^{th} GGI):

$$P_j(t) = -\sum_{i(\neq j)=1}^{3} P_i(t)$$

$$X_j(t) = -\sum_{i(\neq j)=1}^{3} X_j(t)$$

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SINGLE-PAIR GRADIENTS TECHNIQUE (CONT)

INTRODUCE

$$P_i^{(j)}(t) = \begin{cases} P_i(t) & i \neq j \\ -\sum\limits_{k(\neq j)=1}^{3} P_k(t) & i = j \end{cases} \qquad X_i^{(j)}(t) = \begin{cases} X_i(t) & i \neq j \\ -\sum\limits_{k(\neq j)=1}^{3} X_k(t) & i = j \end{cases}$$

(SUPERSCRIPTS DENOTE THE SIMULATED GGI.) THE GRADIOMETER CONSTRAINTS IMPLY THE 'SIMULATION ERRORS'

$$\delta P_i^{(j)}(t) = 0$$

$$\delta X_i^{(j)}(t) = -\tfrac{3}{2}\,\Gamma_{DD}(t)\,\delta_{ij}$$

$$i,j = 1,2,3$$

o WHEN THE THREE-GGI TECHNIQUES ARE USED, THE 'SIMULATION ERROR' APPEARS AS AN INSTRUMENT ERROR, BUT OF VERY DIFFERENT STOCHASTIC PROPERTIES. THESE TECHNIQUES ARE DETERMINISTIC IN NATURE (E.G. ERROR MEASUREMENT $\longrightarrow$ COMPENSATION) AND INVOLVE NO STATISTICAL ESTIMATION: THIS USAGE IS CONCEPTUALLY VALID

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SINGLE-PAIR GRADIENTS TECHNIQUE (CONT)

- THE ERRORS PRODUCED ARE: $\delta X^{(i)}(t) = -\frac{1}{2}\Gamma_{DD}(t)$

$$\delta U_1^{(i)}(t) = -\frac{1}{\sqrt{6}}\,\delta C_{23}^{(i)}(t,0)$$

$$\delta U_2^{(i)}(t) = \frac{1}{\sqrt{3}}\,\delta C_{23}^{(i)}(t,0)$$

$$\delta V_1(t) = \frac{1}{3\sqrt{2}}\left[\delta C_{12}^{(i)}(t,0) - \delta C_{31}^{(i)}(t,0)\right]$$

$$\delta V_2(t) = \frac{1}{3}\left[\delta C_{12}^{(i)}(t,0) - \delta C_{31}^{(i)}(t,0)\right]$$

WHERE

$$\delta C_{i,i+1}^{(i)}(t,0) = -\frac{3}{2}\Gamma_{DD}(t)\left(\delta_{ji} - \delta_{j,i+1}\right) .$$

ALL OTHER ERROR TERMS VANISH

- THE MODULATED ERRORS ARE ESTIMATED BY A PROCEDURE SIMILAR TO THAT OF PART IV

- WRITE $\quad X_i^{(j)}(t) = \underset{\sim}{M}^{(i)T}(\psi_i(t))\,\underset{\sim}{S}_x(t) \qquad i,j = 1,2,3$

SINGLE-PAIR GRADIENTS TECHNIQUE (CONT)

$$\underset{\sim}{M}^{(j)}(\psi_i(t)) = \underset{\sim}{M}(\psi_i(t)) - 3\underset{\sim}{u}\,\delta_{ij}$$

THE ANALYSIS OF PART IV IS REPEATED TO OBTAIN

$$\delta C^{(j)}_{i,i+1}(t,0) = C^{(j)}_{i,i+1}(t, T_c/3) - \underset{\sim}{M}^{(j+2)^T}(\psi_i(t))\left[\Delta_{T_c/3}\,\underset{\sim}{S}_x(t)\right]$$

- THE SECOND TERM IS ELIMINATED AS BEFORE BY EITHER ONE OF:

(1) LOW PASS FILTERING

$$\delta C^{(j)^{LF}}_{i,i+1}(t,0) = \overline{C^{(j)}_{i,i+1}(t, T_c/3)}$$

(2) FEEDING BACK THE NED GRADIENT MEASUREMENTS AND DIRECTLY CALCULATING/COMPENSATING THE TERM

THE SECOND ALTERNATIVE IS PREFERABLE:

$$C^{(j)}_{i,i+1}(t, T_c/3) = -\frac{3}{2}\Gamma_{DD}(t)\left(\delta_{ji} - \delta_{j,i+1}\right)$$

HAS DESIRED HIGH FREQUENCY SIGNATURE CONTENT

SINGLE-PAIR GRADIENTS TECHNIQUE (CONT)

- A MEASUREMENT OF THE REQUIRED ERROR IS OBTAINED

$$\delta C^{(i)}_{i,i+1}(t,0) = C^{(i)}_{i,i+1}(t, T_c/8)$$

AND USED TO COMPENSATE THE MODULATED 'SIMULATION ERROR'. THE TRANSFORMATION YIELDS

$$\begin{bmatrix} \dot{\Gamma}^{(i)}_{NN}(t) \\ \Gamma^{(i)}_{EE}(t) \\ \Gamma^{(i)}_{NE}(t) \\ \Gamma^{(i)}_{ND}(t) \\ \Gamma^{(i)}_{ED}(t) \end{bmatrix} = \begin{bmatrix} \Gamma_{NN}(t) - \delta X^{(i)}(t) \\ \Gamma_{EE}(t) - \delta X^{(i)}(t) \\ \Gamma_{NE}(t) \\ \Gamma_{ND}(t) \\ \Gamma_{ED}(t) \end{bmatrix}$$

- NOTICE THAT

(1) THE FOLLOWING ERROR FREE GRADIENTS HAVE BEEN OBTAINED

$$\Gamma^{(i)}_{NN}(t) - \Gamma^{(i)}_{EE}(t), \quad \Gamma^{(i)}_{NE}(t), \quad \Gamma^{(i)}_{ND}(t), \quad \Gamma^{(i)}_{ED}(t)$$

(2) THE DIAGONAL GRADIENTS CONTAIN THE 'SIMULATION ERROR'

$$\delta X^{(i)}(t).$$

SINGLE-PAIR GRADIENTS TECHNIQUE (CONT)

- THE ERROR FREE GRADIENTS MAY BE USED TO COMPUTE $\delta X^{(j)}(t)$ AND COMPENSATE THE GRADIENTS

  - FOR $i \neq j$

$$X_i^{(j)}(t) = X_i^{(j)*}(t) + \frac{1}{2}\Gamma_{DD}(t) = X_i^{(j)*}(t) - \delta X^{(j)}(t)$$

$$X_i^{(j)*}(t) = \begin{bmatrix} 0 \\ \sin\psi_i(t) \\ \cos\psi_i(t) \\ \sin 2\psi_i(t) \\ \cos 2\psi_i(t) \end{bmatrix}^T \begin{bmatrix} 0 \\ \sqrt{2}/3\,\Gamma_{ED}^{(j)}(t) \\ \sqrt{2}/3\,\Gamma_{ND}^{(j)}(t) \\ 2/3\,\Gamma_{NE}^{(j)}(t) \\ 1/3\left(\Gamma_{NN}^{(j)}(t) - \Gamma_{EE}^{(j)}(t)\right) \end{bmatrix}$$

IS COMPUTED FROM THE ERROR-FREE GRADIENT. $X_i^{(j)}(t)$ IS A DIRECT INSTRUMENT MEASUREMENT. THEN,

$$\delta X^{(j)}(t) = X_i^{(j)*}(t) - X_i^{(j)}(t)$$

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SINGLE-PAIR GRADIENTS TECHNIQUE (CONT)

- RESULT IS INDEPENDENT OF THE GGI $i(\neq j)=1,2,3$. TWO SUCH MEASUREMENTS OF $\delta X^{(j)}(t)$ ARE OBTAINABLE FOR EACH j. IN THE GENERAL CASE OF NONVANISHING ERRORS, WEIGH THE TWO MEASUREMENTS TO ESTIMATE

$$\delta \hat{X}^{(j)}(t) = \sum_{i(\neq j)=1}^{3} W_i(t) \left[\hat{X}_i^{(j)*}(t) - \hat{X}_i^{(j)}(t) \right]$$

WEIGHTS CAN BE OBTAINED FROM THE INSTRUMENT ERROR ESTIMATES (E.G. VARIANCES) OF THE PERFORMANCE MONITORING FUNCTION. THIS WILL OPTIMIZE THE LOW FREQUENCY ERROR CONTAMINATION OF THE DIAGONAL GRADIENTS.

- THE CORRECTION $\delta X^{(j)}(t)$ IS APPLIED TO THE PREVIOUS GRADIENT ESTIMATE. THE FINAL ESTIMATE OF THE j^{th} PAIR-GRADIENTS IS:

$$\left[\Gamma_{NED}^{(j)}(t) \right] = \begin{bmatrix} \Gamma_{NN}^{(j)}(t) \\ \Gamma_{EE}^{(j)}(t) \\ \Gamma_{NE}^{(j)}(t) \\ \Gamma_{ND}^{(j)}(t) \\ \Gamma_{ED}^{(j)}(t) \end{bmatrix} = \begin{bmatrix} \Gamma_{NN}(t) \\ \Gamma_{EE}(t) \\ \Gamma_{NE}(t) \\ \Gamma_{ND}(t) \\ \Gamma_{ED}(t) \end{bmatrix}$$

PART VII: THREE-PAIR GRADIENT TECHNIQUE

- THE THREE-PAIR GRADIENT TECHNIQUE CONSISTS OF REPEATING (IN PARALLEL) THE PREVIOUSLY DESCRIBED ALGORITHMS TO OBTAIN THREE SIMULTANEOUS MEASUREMENTS OF NED GRADIENTS. IN GENERAL, THESE MEASUREMENTS ARE NOT ERROR-INDEPENDENT. THE FOLLOWING COMMENTS APPLY TO THIS GENERAL CASE.

- THE INTEGRATION OF THE ERROR ESTIMATION/COMPENSATION TECHNIQUE (PARTS IV, V) AND THE PAIR-GRADIENT TECHNIQUE (PART VI) IS NOT VERY STRAIGHTFORWARD. THE ERROR ANALYSIS OF PART IV BECOMES TOO INVOLVED AND WILL NOT BE PRESENTED HERE.

    - ILLUSTRATION: THE INSTRUMENT PERFORMANCE MONITORING FUNCTION (PART V) ASSUMED THAT INSTRUMENT ERRORS WERE UNCORRELATED; THIS IS NOT CORRECT WITH THE 'SIMULATED GGI' OUTPUTS.

THREE-PAIR GRADIENT TECHNIQUE (CONT)

- THE BASIC CONCEPTS PREVIOUSLY PRESENTED ARE STILL VALID. WITH MINOR MODIFICATIONS, THE TWO TECHNIQUES CAN BE INTEGRATED INTO A FULLY REAL-TIME THREE-PAIR GRADIENT ALGORITHM. THIS OBTAINS EACH TIME t THREE SET OF NED GRADIENTS

$$\left[\hat{\Gamma}^{(j)}_{NED}(t)\right] \quad j = 1, 2, 3$$

WITH THE FOLLOWING PROPERTIES

(1) $\delta\Gamma^{(i)}_{NE}(t)$, $\delta\Gamma^{(i)}_{NN}(t) - \delta\Gamma^{(i)}_{EE}(t)$, $\delta\Gamma^{(i)}_{ND}(t)$, $\delta\Gamma^{(i)}_{ED}(t)$ ARE WHITE NOISE PROCESSES OF MAGNITUDE COMPARABLE TO THE INSTRUMENT WHITE NOISE LEVEL

(2) $\delta\Gamma^{(i)}_{NN}(t) + \delta\Gamma^{(i)}_{EE}(t) \left(= -\delta\Gamma^{(i)}_{DD}(t)\right)$ CONTAINS, IN ADDITION TO THE ABOVE WHITE NOISE, A LOW FREQUENCY CONTAMINATION EQUAL TO THE (WEIGHTED) AVERAGE OF THE LOW FREQUENCY ERRORS OF THE TWO INSTRUMENTS $i(\neq j) = 1, 2, 3$

- THIS ERROR CAN BE MINIMIZED FURTHER BY COMPUTING THE FINAL NED GRADIENT ESTIMATE AS THE WEIGHTED AVERAGE OF THE THREE PAIRS:

$$\left[\Gamma_{NED}(t)\right] = \sum_{j=1}^{3} W_j(t) \left[\Gamma^{(j)}_{NED}(t)\right]$$

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THREE-PAIR GRADIENT TECHNIQUE (CONT)

WEIGHTS CAN BE COMPUTED IN REAL-TIME FROM THE ESTIMATES OF INSTRUMENT LOW FREQUENCY PERFORMANCE

- THE WEIGHTS CAN ALSO BE DISCRETE

$$\left(W_1(t), W_2(t), W_3(t)\right) = \begin{cases} (1/3, 1/3, 1/3) \\ (1, 0, 0) \\ (0, 1, 0) \\ (0, 0, 1) \\ (0, 0, 0) \end{cases}$$

AND DETERMINED BY

(1) EDITING FUNCTION

(2) MONITORING FUNCTION

THREE-PAIR GRADIENT TECHNIQUE (CONT)

(3) HARDWARE STATUS

(4) STATUS OF MOVING BASE

- THE WEIGHTING TECHNIQUE INTRODUCES A NON-HARMONIC MODULATION OF THE LOW FREQUENCY ERROR IN $\delta\Gamma_{NN}(t) + \delta\Gamma_{EE}(t)$. SEPARATE ERROR-MODELING IS REQUIRED
  - o IN THE CASE OF DISCRETE WEIGHTS: THE DIAGONAL GRADIENTS EXPERIENCE JUMP DISCONTINUITIES IN LOW FREQUENCY ERRORS INCLUDING RAMPS AND BIASES. THIS IS UNDESIRABLE (DISCONTINUITIES ARE NOT DISTINGUISHABLE IN REAL TIME FROM GRAVITY SIGNATURE)
  - o A TECHNIQUE CAN BE DEVISED TO MEASURE THE JUMP DISCONTINUITIES IN REAL TIME AND COMPENSATE THE GRADIENTS ACCORDINGLY; FURTHER DISCUSSION OF THIS IS BEYOND THE SCOPE OF THIS PRESENTATION

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PART VIII: CONCLUSION

- IN SUMMARY, IT IS OBSERVED THAT

  (1) INSTRUMENT ERRORS HAVE BEEN HANDLED DETERMINISTICALLY (MEASUREMENT/COMPENSATION PROCESS)

  (2) THE OPTIMIZATION PROCEDURE OF PART IV HAS ALSO BEEN HANDLED DETERMINISTICALLY

  (3) A FULL SET OF TWO-SENSOR LOCAL LEVEL GRADIENTS CAN BE OBTAINED OF QUALITY IN GENERAL COMPARABLE TO THAT OF THREE SENSORS

  THEREFORE, THE TECHNIQUES PRESENTED PROVIDE THE BEST POSSIBLE SET OF LOCAL LEVEL GRADIENTS THAT CAN BE OBTAINED FROM THE BELL GRADIOMETER WITHOUT THE AID OF INFORMATION EXTERNAL TO THE SYSTEM (E.G. GRAVITY MAPS, GRAVITY MODELS, LOCATION)

- THIS CONCLUSION HAS BEEN TESTED: THE ALGORITHMS HAVE BEEN APPLIED TO THE DATA FROM THE GRADIOMETER ABOARD THE NAVY'S NAVIGATION TEST VEHICLE (USNS VANGUARD) OBTAINED DURING VARIOUS TEST PERIODS

CONCLUSION (CONT)

- GRADIENTS OBTAINED BY THIS TECHNIQUE WERE FED INTO A VERTICAL DEFLECTION ESTIMATION ALGORITHM AND THE RESULTS WERE COMPARED TO EXISTING HIGH ACCURACY MAPS
- IMPROVEMENTS OF 20-45% WERE OBSERVED IN THE VERTICAL DEFLECTION ESTIMATION ERROR OVER OTHER GRADIENT ESTIMATION TECHNIQUES (INCLUDING POST-TIME ONES)
- THE IMPROVEMENTS WERE ESPECIALLY SIGNIFICANT IN PERIODS OF HIGH GRAVITY SIGNATURE (ACTIVE REGIONS, RANDOM SHIP MANEUVERS) AND DURING TESTS INVOLVING VERY NOISY INSTRUMENTS (HIGH SEA STATES, HIGH INSTRUMENT SENSITIVITIES)